Gear Grinding Fundamentals

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Introduction

This article deals with certain items to be taken into consideration for gear grinding, common problems that arise in gear grinding and their solutions. The discussion will be limited to jobbing or low-batch production environments, where experimental setup and testing is not possible for economic and other reasons.

Gear grinding is basically performed either to finish hardened gears or to enhance the accuracy of gears or both. The accuracy from gear grinding includes desired lead and profile modifications, lower spacing and runout errors, and high surface finish. Most of the time, gear grinding is associated with case-hardened gears where teeth have been cut before heat treatment, but through-hardened gears are also ground for higher accuracies. In the case of fine pitch gears, many times teeth are ground in a finished blank without any previous teeth cutting operation.

Gear Grinding Preparation

Following are some of the items which should be considered carefully in detail for successful gear grinding.

Preparation of the Gear Blank. The common statement, "A good gear blank is

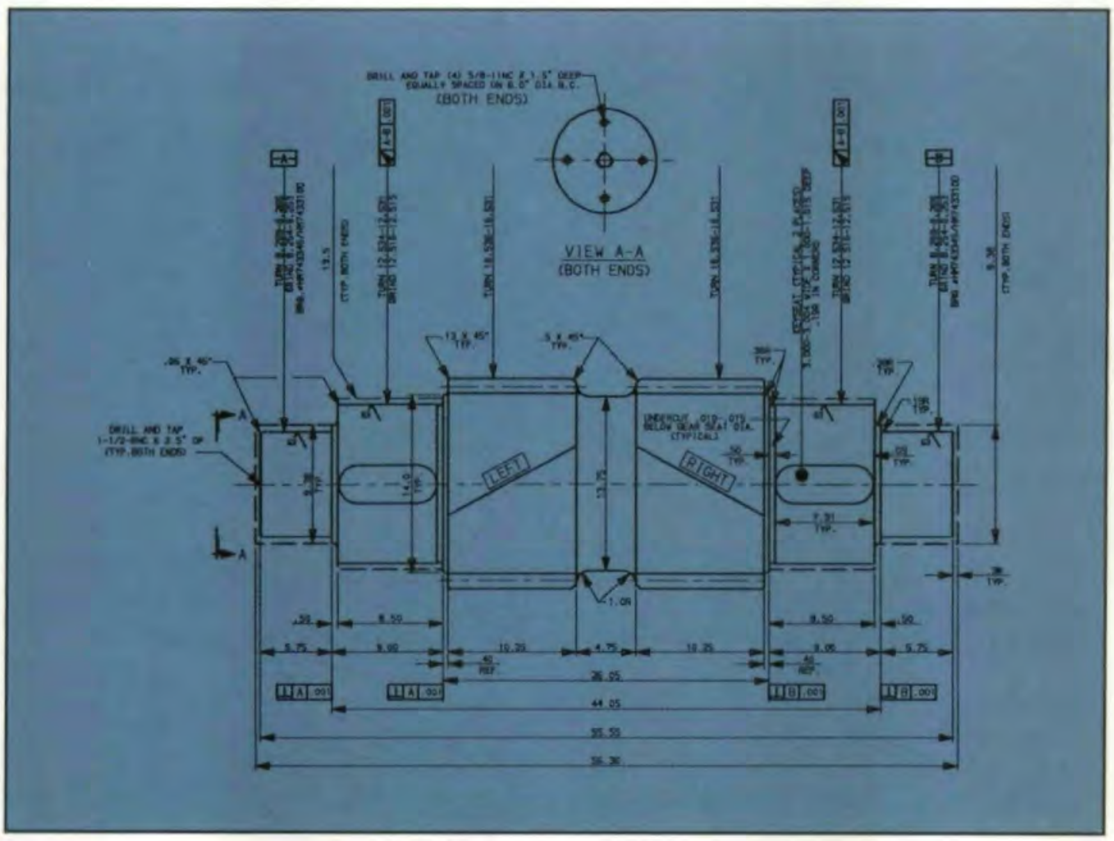

Fig. 1 – Double helical pinion shaft showing groove for grinding wheel clearance.

a must for a good gear," is very true for a successful gear grinding operation. As gear grinding is quite often the last operation in gear manufacturing, any compromise in gear blank design, processing, or manufacturing can cause unnecessary delays, poor quality, or rejected parts.

The following items should be considered for gear blank preparation.

Grinding Wheel Runout Clearance at Tooth Grinding. Gear blanks with constraints on one or both ends must be checked for proper grinding wheel clearance. These include double helical gears, pinion shafts with teeth running out in diameters higher than root diameter, etc.

The grinding wheel runout clearance is a function of many factors, such as grinding wheel diameter, helix angle, DPN, etc., but the grinding wheel diameter is the most influential item. One of the simple solution approaches is to provide designers a chart for runout clearance based on DPN, helix, and grinding wheel diameters on available machines, along with a machine capacity chart. This will allow designers to have a preliminary design with a reasonable accuracy, which must be verified by an appropriate person in manufacturing. Runout clearance values can also be included in gear design programs and provided to the designer with gear data. In cases of critical application, runout clearance can be fine tuned with dummy blanks on grinding machines.

Fig. 1 shows a double helical pinion; Fig. 2 shows a pinion shaft with runout

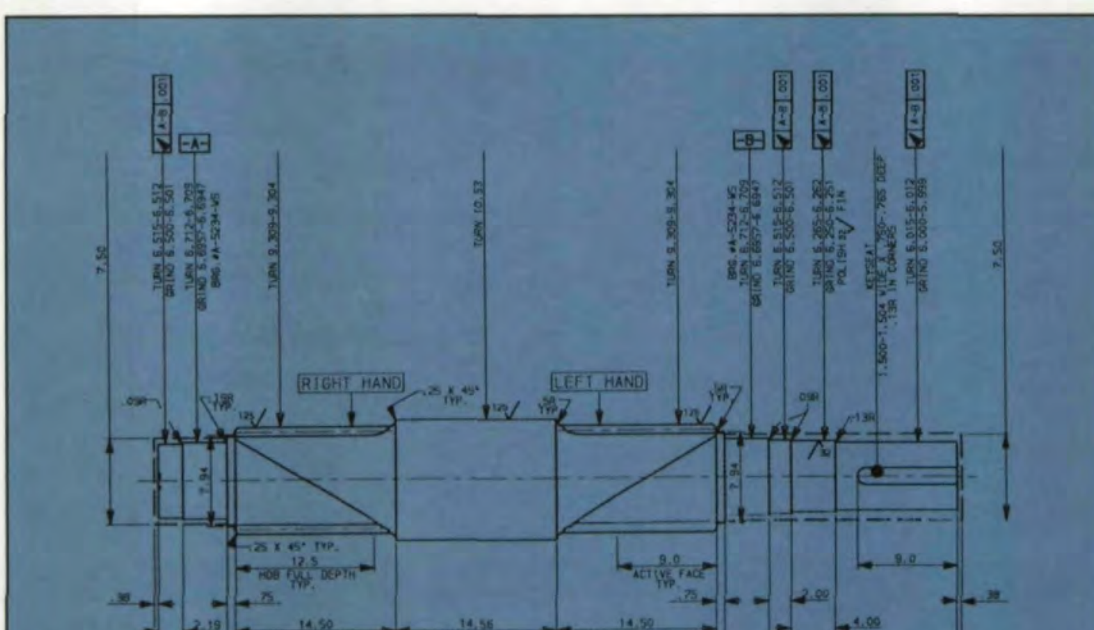

Fig. 2 – Double helical pinion shaft showing runout for grinding wheel clearance.


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clearance for a grinding wheel, and Fig. 3 shows suggested values for double helical gear groove widths.

Selection of Proper Blank Tolerances. The tolerances of the blank, such as TIR of mounting or locating bore, squareness of the bore with mounting surface, etc., must be decided based on all related factors, including quality requirements. Fig. 4 shows some of these values on a simpler gear blank.

Preparation of Any Sub-Assembly Before Tooth Grinding. Fig. 5 shows a subassembly of a gear with a shaft. As in any final machining operation, prior subassembly work is quite helpful in achieving higher accuracies.

As shown in this sketch, if the teeth are ground after sub-assembly, the runout and squareness problems are minimized. These two problems arise because tolerances add up if the gear and shaft are sub-assembled after gear grinding.

Proper Indicating Proof Surfaces or Bands on Gear Blanks. Proof surfaces, a critical item in gear grinding, must not be overlooked. A gear reaching the tooth grinding stage without proper indicating surfaces can cause unsatisfactory quality and long delays. Fig. 6 shows an example of a gear with proof surfaces.

Blank Inspection Before Tooth Grinding. In certain critical applications, gear blanks must be checked for required values of runout and squareness of mounting surfaces to avoid poor quality and excessive delays. Random checks must be done on all work prior to tooth grinding.

Selection of Proper Quality Number. AGMA standard 390.03 is the most common gear quality reference guide in use in the U.S. The selection of proper quality class number is quite critical, as a lower number will not meet the design requirements, while a higher number will increase the cost. The selection of proper quality number should be made based on past experience, application, limitations of grinding machines, and many other factors.

Wherever possible, desired lead and profile charts should be defined clearly to avoid any confusion at gear grinding. The

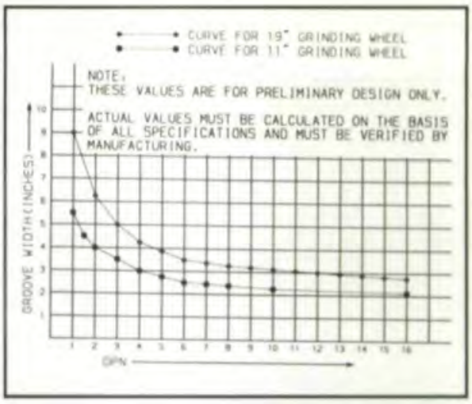

Fig. 3 – Groove width for double helical gears.

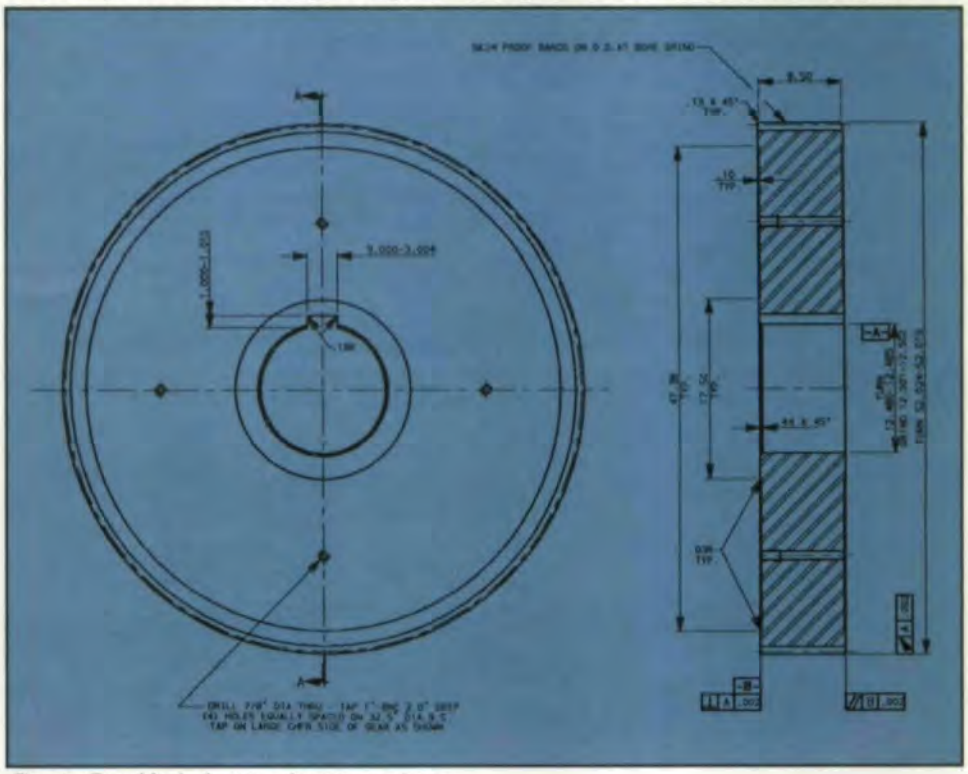

Fig. 4 – Gear blank drawing showing machining tolerances.

cost of tooth grinding increases at a much faster rate at higher quality levels than at lower levels. In other words, the cost of changing the quality number 10 to 11 is lower than changing 12 to 13. Cost is not the only factor to be considered. As quality number rises, the number of tooth grinding machines available to achieve the higher quality decreases, causing many other problems.

The matched sets approach is quite advantageous in high precision gears. In matched sets, the gear and pinion profiles and leads are matched in such a way that mismatch in a set does not exceed the tolerance on lead or profile for the applicable quality number. In matched sets conditions, one member, most frequently a gear with a higher number of teeth, is ground first and checked. The lead and profile charts are studied carefully, and modifications to achieve the desired match are made in the tooth grinding of the matching member. One disadvantage of matched sets is that any replacement in the future has to be made in sets, but on the other hand, in any critical application, replacement of one member is not desired anyhow. Also, in the case of matched sets, clear detailed advanced agreements between user and supplier can eliminate unnecessary misunderstandings and delays.

In some special cases, certain tolerance relief can be allowed in specific gear quality elements, which may reduce corrections at tooth grinding. Some examples are lead-in drives with eccentric cartridges and profile and lead-in hardened pinions over 55 Rc running with through-hardened gear less than 40 Rc.

Grinding Allowance and Heat Treatment. In simple words, grinding allowance in tooth grinding is extra material left on tooth flanks (and fillet, in cases where the fillet is to be ground). It is required to grind the tooth surfaces to proper profile, lead and other quality elements within specified tooth sizes. Excessive grind allowance causes many problems, such as longer grind time, loss of case depth, etc. On the other hand, insufficient grind allowance will result in undersize tooth thickness. Improper grind allowance (excessive or insufficient) will cause many problems, such as

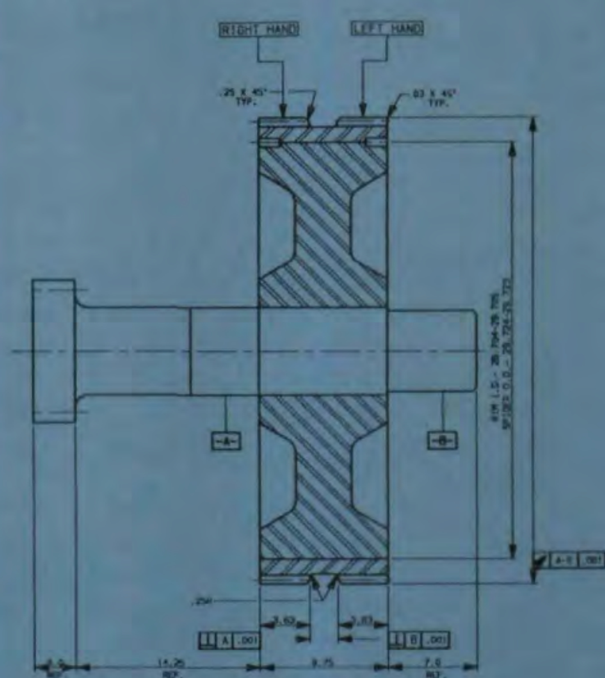

Fig. 5 – Sub-assembly gear and shaft.

higher costs, longer delays, and rejected parts in extreme cases or critical applications.

Following are some factors influencing grinding allowance.

Heat Treatment Method. The heat treatment method is very influential in selecting the amount of gear grinding allowance. Below are the commonly used heat treatment methods for gear teeth.

1. Case carburizing and hardening
2. Induction hardening (tooth-to-tooth and coil)
3. Case nitriding
4. Through-hardening

The distortions in nitriding are very low; whereas, they are quite predictable in the induction hardening process. Case carburizing and hardening distortions are quite complicated and magnify with size and shape. Many factors, such as design, material machining before heat treatment, shape of part, fixturing in carburizing, quenching, and machining after heat treatment, influence what a gear grinder will see when he makes a touch on a grinding machine.

Any compromise in one or more factors, affects the final outcome. Most of the factors are so interrelated and interconnected that many times the investigation and corrections are carried out at the wrong point. One of the most effective methods is to start with a completely open mind and record the results after every operation.

Machining of gears after heat treatment and before tooth grinding is very critical and must not be overlooked or neglected. A gear can be checked for runout in the plane of rotation on a turning or grinding machine with a roller in teeth, but there is no easy means of checking teeth in an axial plane. Quite often, overcorrections are made in one plane, causing extra problems in the other plane. One effective approach is to indicate proof surfaces created in machining before cutting and used in cutting in both planes. Another very effective method is to turn or grind proof surfaces after hardening and check the gear for runout and lead. Finish machine the gear bore and faces or shaft journals after making corrections based on runout and lead

Fig. 6 – Gear with proof surfaces.

charts, relative to proof surfaces created after hardening and used for setting on gear checking machines. The above method is effective, but needs two extra operations and a longer cycle. Also it is ineffective when a gear has irregular distortions, such as taper along length or oval shape of diameter.

Gear Blank Configuration. A well proportioned configuration of gear or pinion shaft will have fewer distortions in heat treatment. On the other hand, poor design will cause excessive distortions. Sometimes application or weight limitations make a blank unsuitable for case-carburizing and hardening. (See Fig. 6.) The above situation can be handled in a number of ways: either leave extra material all around or use quench press in final quenching. The use of quench presses with univeral dies in a jobbing enviroment needs much more planning and estimation than in mass or high production environments. In high production, customized dies are prepared and tested on sample pieces with different adjustments on quench press, and setups are completely optimized for production. On the other hand, a jobbing environment does not allow detailed testing or customized tooling. Whenever there is more than one piece in a batch, the first piece should be die quenched and measured before quenching the rest of the pieces, allowing the tool modification and setup adjustments for better results. Another recommended approach in quenching is to start with a lower clamp and expand pressures rather than high values, which may cause excessive growth, resulting in various problems at tooth grinding. (See Fig. 7.)

Tooth Size. DPN or module, helix angle, outside diameter, face width, etc., all affect the amount of grinding allowance required. For example, the working depth on a 2 DPN is twice that on a 4 DPN tooth.

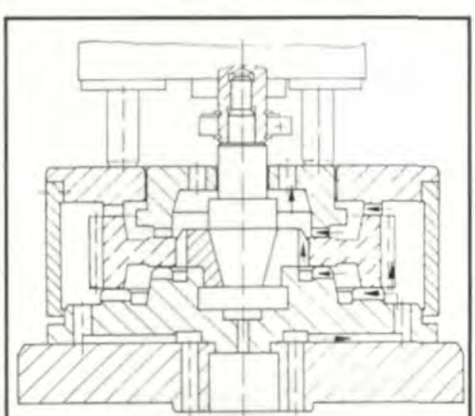

Fig. 7 – Quenching a cylindrical gear with special configuration. (Courtesy Klingelnberg Corporation.)

Gear Application. Certain applications need much tighter control on tooth thickness than others. In the case of an application with tighter tooth thickenss requirements, higher grind allowances can avoid tooth thickness problems at tooth grinding.

Some other factors affecting grind allowance are gear cutting operation and equipment, gear grinding equipment, gear quality requirements, etc.

Selection of Proper Cutting Tools. High production allows the use of customized tools with optimized grinding allowance and protuberance, while low quantity production imposes the use of universal tooling as much as possible. The following steps are suggested to maximize the use of pre-grind tools with best possible conditions at gear grinding.

a. Standardize fillets for all new designs and use them wherever possible. Fig. 8 shows a comparison of standard fillets and full fillets.
b. Select and standardize grinding allowance on the basis of various factors discussed previously.

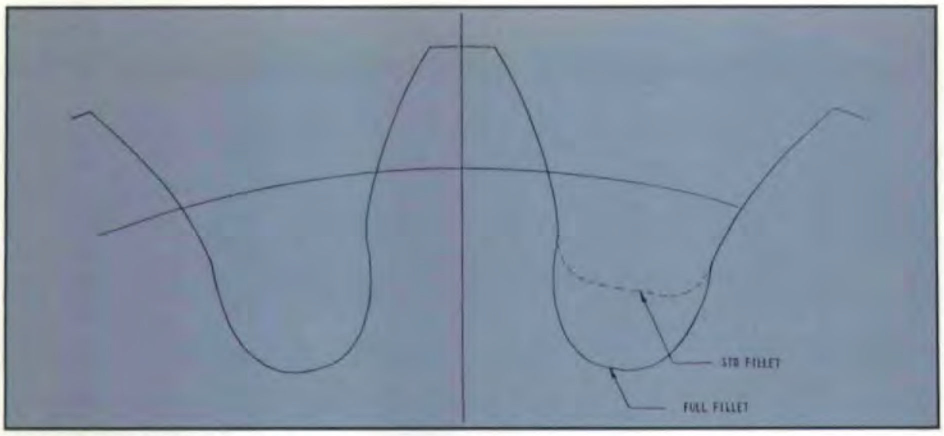

Fig. 8 – Standard fillet vs full fillet.

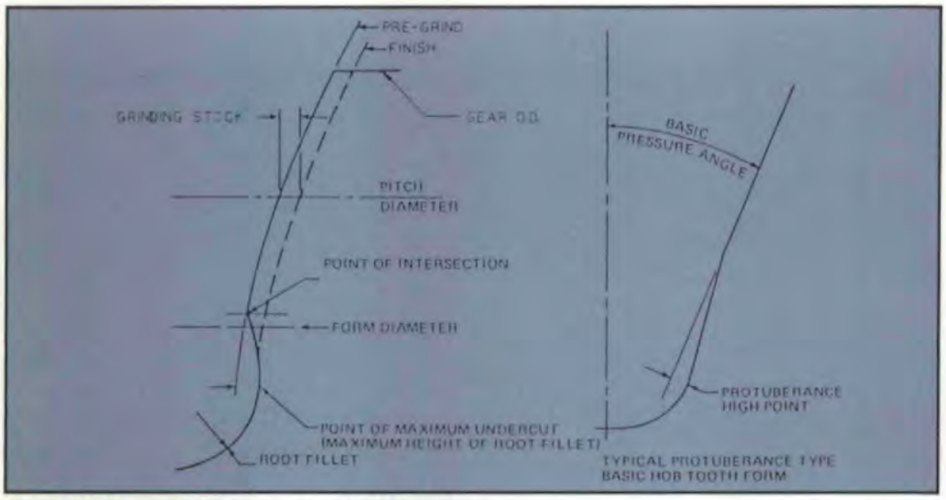

Fig. 9 – Undercut produces by a pre-grind hob and a protuberance type hob.

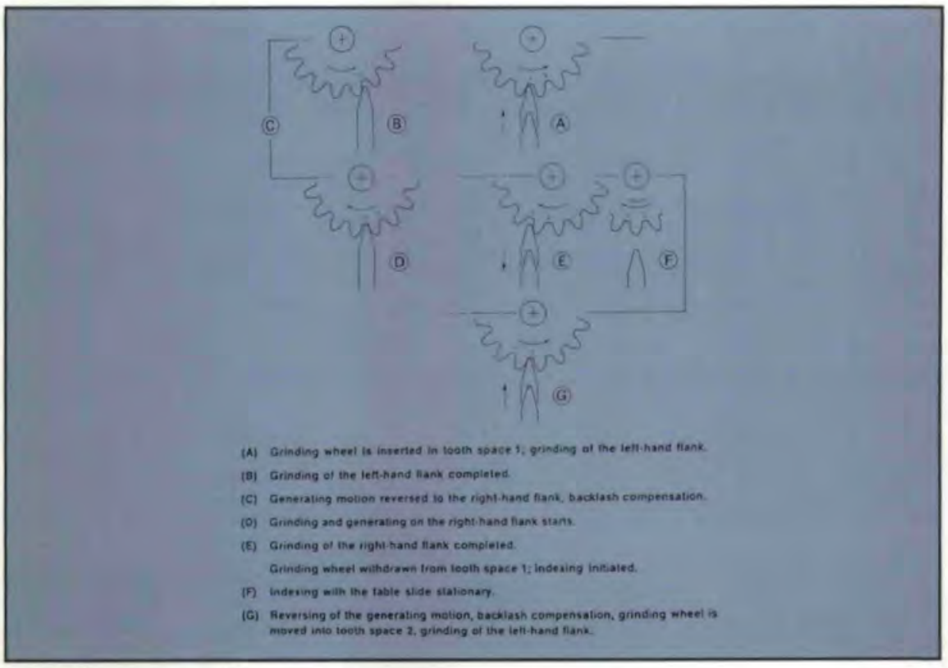

Fig. 10 – Representation of the gear grinding process. (Courtesy of BHS Hofler, Ettlingen, West Germany.)

c. Select protuberance on the basis of DPN. Excessive protuberance on gear cutting tools can cause unclean profile above TIF (SAP) at tooth grinding, while insufficient protuberance can cause grinding step problems. Fig. 9 shows undercut produced by a pre-grind hob and a protuberance type hob.
d. Adjust the thickness of all pre-grind tools on the basis of grinding allowance.

The universal tool selection always causes certain shortcomings at tooth grinding, and constant monitoring must be done to avoid major problems.

The importance and necessity of customized tooling for all critical and special applications cannot be overemphasized. In such cases, an optimized tool always avoids many problems at tooth grinding.

Grinding Process

Tooth grinding of gears can be classified into two main processes: generating grinding and form grinding. In generating grinding, the teeth are ground as the gear rolls in relation to the reciprocating grinding wheel. The process is similar to gear meshing with a straight sided rack. The three most common methods or machines are:

Conical Wheel Machines. As shown in Fig. 10, both flanks are ground independently. After each tooth is completed, the machine indexes to the next tooth until the gear is ground. Desired lead and profile and modifications are made on the machine. The profile is modified by grinding wheel dressing, and lead modifications are obtained through the use of cams.

Saucer Wheel Machines. In this method, the gear being ground has oscillating rolling-generating motion, while two grinding wheels sweep out the involute profiles by the relative motion. The two most common methods are 0° grinding method and 15°/20° grinding method.

The two most common types of these machines available are the horizontal type and vertical type, each suitable for different sizes, etc.

Threaded Wheel Machines. Threaded wheel machines operate on the same principle as gear hobbing machines. Threaded wheel machines are quite productive, but have limitations in pitch and overall size.

Form Grinding. This process uses a form grinding wheel to grind both flanks, while the work piece is maintained in a fixed radial position. Form grinding is quite useful in many applications, and both external and internal gears can be ground by this method.

Grinding Wheel Selection. Selection of the grinding wheel is quite important in gear grinding. Following are some of the variables to consider when choosing a grinding wheel. (Fig. 11).

Abrasives. The four main abrasives in use are

a. Aluminum oxide (AL_2O_3
b. Silicon carbide (SC)
c. Cubic Boron Nitride (CBN)
d. Diamond

The use of "cubic boron nitride" is increasing every day. It is still mainly limited to form grinding in gears but much research into its use in grinding is being done. Diamond is rarely used in gear grinding.

The other variables in grinding wheel selection are grit size, grade or hardness, and structure. A properly selected wheel should maintain its form for a reasonable period and produce the required surface finish without burning the tooth surface. Grit that is too hard and fine will maintain its edge and give good surface finish, but material removal is slow and chance of burning is too high. On the other hand, soft and coarse grit will remove metal fast without burning, but the edge wear will be high. The consumption of the soft wheel is also high.

One simple rule of selecting grade or hardness is "the harder the material, the softer the grind wheel and vice versa". To get satisfying results from grinding wheels, the following are suggested.

a. Monitor the performance of the grinding wheel constantly.
b. Maintain good records.
c. Work with a limited number of suppliers.
d. Select the grinding wheel based on heat treatment, pitch, surface finish, and other factors.
e. Continue some kind of program to upgrade the grinding wheels. Besides grinding wheels, the dressers and dressing equipment must be maintained properly.

Coolant for Wet Grinding. The importance of the proper selection of coolant in wet gear grinding must not be underestimated. The use of coolant reduces the grinding wheel loading, lowers

(continued on page 37)

Abrasives Standard Marking System

This chart presents symbols found in a typical grinding wheel specification — they represent the variable components of a grinding wheel. The marking sequence conforms to the standard system used throughout the grinding wheel industry.

9A	46	K	5	V
ABRASIVE TYPE	**GRIT SIZE**	**GRADE**	**STRUCTURE**	**BOND TYPE**

ABRASIVE TYPE

- Reg. Alumn. Oxide — A
- Spec. Alum. Oxide — 2A
- Spec. Alum. Oxide — 3A
- Spec. Alum. Oxide — 5A
- Spec. Alum. Oxide — 8A
- Spec. Alum. Oxide — 16A
- Spec. Alum. Oxide — 17A
- Spec. Alum. Oxide — 19A
- White Alum. Oxide — 9A
- Tough Alum. Oxide — 27A
- Tough Alum. Oxide — BA
- Tough Alum. Oxide — TA
- Reg. Sil. Carbide — C
- Green Sil. Carbide — 1C
- 1/2 Reg. Sil. Carbide 1/2 Green Sil. Carbide — 3C
- Combination of Alum. Oxide and Sil. Carbide — CA, MA

GRIT SIZE

- COARSE: 10, 12, 14, 16, 20, 24
- MEDIUM: 30, 36, 46, 54, 60
- FINE: 70, 80, 90, 100, 120, 150, 180
- VERY FINE: 220, 240, 280, 320, 400, 500, 600

GRADE

- SOFT: C, D, E, F, G, H, I
- MEDIUM: J, K, L, M, N, O, P
- HARD: Q, R, S, T, U, V, W, X, Y, Z

STRUCTURE

- DENSE
- 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11
- KOOLPORE WHEELS
- 12
- KOOLPORE WHEELS
- 13, 14, 15, 16
- OPEN

BOND TYPE

- B=RESINOID
- F=BAYFLEX
- M=METAL
- R=RUBBER
- V=VITRIFIED

Fig. 11 – Standard marking system for abrasives. (Courtesy Bay State Abrasives Division, Abrasive Industries, Inc.)

 (continued from page 35)

operating temperatures, increases grinding wheel life, and gives better surface finish on teeth flanks. The following considerations should be noted when selecting and using a gear grinding coolant.

a. The quality of gear grinding coolant must not be sacrificed in the name of coolant standardization.
b. Gear grinding coolant must be constantly monitored for contamination and dilution.
c. Samples from every machine or system should be taken out, periodically checked, and results recorded.
d. Wind deflectors should be used where necessary.

   The surface speed of a grinding wheel is quite high, causing an envelope of high-speed air to form around it. Consequently, the velocity of coolant must be high enough to penetrate the air layer. The use of a wind deflector is very helpful in this situation.
e. Sparking must be eliminated as soon as it occurs. Sparks during wet grinding usually indicate that coolant is not reaching the required spot in sufficient quantity. It indicates intermittent heating, which is highly undesirable, as it can lead to surface tempering or cracking or both.

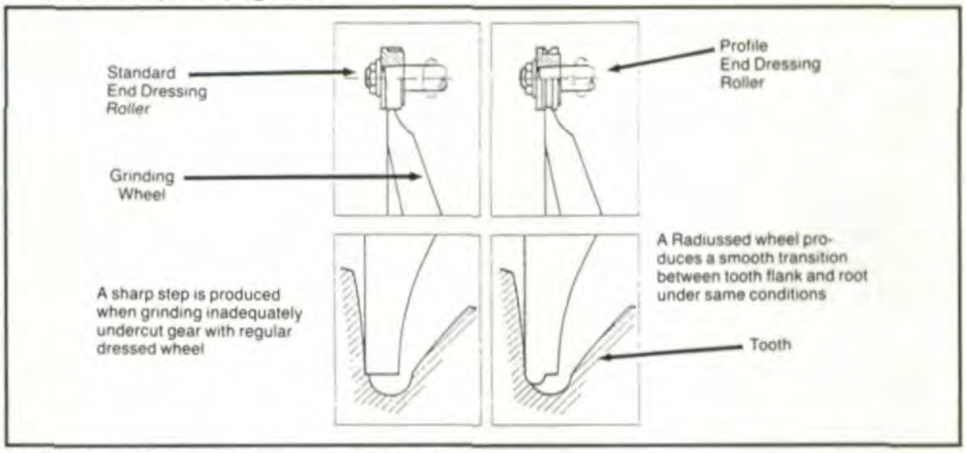

Fig. 12 – End dresser options for saucer wheel grind- ing machines.

Gear Grinding Problems and Suggested Solutions Approach

Gear Grinding Steps. Grinding steps in tooth fillets have various causes and are very detrimental. They act as stress risers and also reduce the critical case depth in tooth fillets. Any subsequent work performed to remove the steps raises the cost and can cause various other problems. Here are some suggested approaches to eliminate or reduce the steps in tooth fillets.

a. Always use a hob with proper protuberance, thickness, blend angle, fillet radius, etc.
b. Use the correct amount of grinding allowance on tooth thickness at cutting.
c. Grind the tooth flank to proper depth. Define and use the point of maximum undercut in grinding setup.
d. Continuously train and educate personnel.
e. Monitor and resolve problems by immediate attention.

Sometimes it will be quite difficult to avoid steps completely, because of excessive distortion at heat treatment, use of improper tools, excessive grinding allowance, etc. In such cases, use of a grinding wheel with tip radius can avoid sharp corners in grinding steps. The amount of radius can be selected on the basis of DPN, grinding machine, and all other factors. The same approach can be used in conical wheel machines. (See Fig. 12.)

Gear Grinding Cracks. Gear grinding cracks or grinding checks usually indicate that there is process control problem, either in heat treatment or in gear grinding or both.

Heat Treatment. The correct amount of case carbon content is very critical, as an insufficient amount can cause low hardness problems; whereas, excessive case carbon content can cause the presence of retained austenite. The grinding process generates pressure and heat, which causes transformation. Retained austenite transformation at grinding is considered a source of surface tempering or cracks or both.

Free carbides or carbide networks in case structures is another side effect of excessive case carbon content. Excessive hardness of the material (free carbides) can cause localized overheating. Overheating during the grinding operation results in surface tempering or cracks or both.

Heat treatment operations usually result in some film on the surface of heat treated parts. This scale must be removed before grinding, as it tends to load the grinding wheel. Surface oxidation in heat treatment produces a thin layer of decarburized and soft material on teeth flanks. This material loads up the grinding wheel, causing overheating, leading to surface tempering or cracks or both.

Excessive distortions in an irregular pattern make it difficult for machine operators to locate the highest point on the gear tooth surface. If the grinding cut is not started at this point, excessive amounts of material will be removed during the cut from high points. Excessive cuts will generate overheating and can lead to cracking or surface tempering or both. This problem can be handled easily by the machine operator on a machine with threaded wheels and continuous indexing.

Gear Grinding. The variables in gear grinding operations are the gear grinding machine, the grinding wheel, the grinding coolant in the case of wet grinding, and grinding machine setup.

Any problem with one or more variables can lead to various problems, including cracks on teeth. As discussed before, overheating or excessive heating at any point in the grinding operation can lead to surface tempering or grinding cracks or both. This overheating can be caused by a combination of factors, such as malfunction of the gear grinding machine, use of an improper grinding wheel, unsuitable coolant or improper positioning of coolant nozzle, and an excessive amount of cut or material removal.

Gear Grinding Cost. In a jobbing or low batch production, gear grinding cost is an important matter. The estimation is normally based on many factors in grinding, such as number of teeth, DPN, helix angle, face, material, grinding allowance, quality, method, machine, etc., and the final number is corrected on the basis of past experience. Somehow, the estimation usually falls short of actual time. In the current competitive world, the gear grinding cost has to be maintained at a reasonable level. Below are some suggested approaches.

a. Setup preparation cannot be overemphasized in a low production atmosphere. It is a good practice to have more than one item ready for the grinding machine. In case something goes wrong at the last minute with the first item on line, the next on line can be started without excessive idle time.
b. Heat treatment distortions or metallurgical characteristics and inadequate manufacturing process control will deliver gears with high inaccuracies to gear grinding, which will increase grinding time. Therefore, a good control at heat treatment and manufacturing process will not only cut grinding times, but will also reduce scrappage and enhance quality.
c. A good preventative maintenance of gear grinding machines will keep downtime minimum.
d. Training and education of personnel is quite critical and must not be overlooked.
e. Use of skiving hobs can be very helpful in many ways, such as removing most of the distortions and delivering a gear to grinding with limited grind allowance, reducing grinding time, removing any heat treatment scale or decarburized and soft layers of material from teeth flanks, reducing the possibility of the surface tempering or grinding cracks or both.

Miscellaneous

Stress Relieving After Tooth Grinding. A stress relieving operation after tooth grinding is highly desirable in all critical applications. This stress relieving minimizes the possibility of latent grinding cracks. Latent grinding cracks are the cracks that develop in the storage or early period of use. The typical stress relieving for case-carburized and hardened parts is around 320°F for four hours, which can be further refined for every application. This stress relieving must be carried out as soon as possible after tooth grinding, as any excessively delayed stress relieving may be too late.

Grinding Allowance at Tooth Cutting. As discussed earlier, excessive grinding allowance causes many problems. To avoid excessive material left at teeth cutting, all cutting personnel should be trained, parts must be checked, and sizes recorded after teeth cutting. In cases where Q.C. personnel are not available, these steps can be taken by shop supervisors.

Use of a Quench Press. The use of a quench press with proper setup can keep distortions well in control. Many complicated parts can be pre-machined to suit quench press use.

Prequenching and Tempering. Prequenching and tempering of rough-turned gear blanks can be advantageous in stabilizing and estimating growth of a gear in final heat treatment.

Checking. All ground parts must be checked for cracks after grinding. It is also very important to do frequent magnaflux inspection during the grinding operation, particularly in case of a large batch or big gears, to catch any problem at an early stage.

Handling of Gears With Grinding Cracks. Any part with severe grinding cracks or surface tempering cannot be salvaged. The suggested approach for parts with minor problems include: stress relief, regrinding to remove cracks, magnaflux inspection for cracks, checking final tooth sizes, and reporting all findings to the engineering department for disposition.

Gears With Close Tooth Thickness Tolerances. Many applications need close tooth tolerances. A practical approach is to keep an approved master in the same environment as gears being ground and compare sizes. For the most part, the first piece of a batch can be used as a master after complete inspection.

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