Gear Grinding Comes of Age

What you need to know about wheels and abrasives now.

Phillip Plainte

In the quest for ever more exacting and compact commercial gears, precision abrasives are playing a key production role—a role that can shorten cycle time, reduce machining costs and meet growing market demand for such requirements as light weights, high loads, high speed and quiet operation. Used in conjunction with high-quality grinding machines, abrasives can deliver a level of accuracy unmatched by other manufacturing techniques, cost-effectively meeting AGMA gear quality levels in the 12 to 15 range. Thanks to advances in grinding and abrasive technology, machining has become one of the most viable means to grind fast, strong and quiet gears.

The Evolution of Grinding

Traditional gear grinding was a slow, expensive process that required complex machines and highly skilled operators, a process considered appropriate for only the closest-tolerance applications, such as aerospace. Engineers would develop performance-enhancing tooth geometry changes using prototype ground gears, then purchase tooling for shaving production. Now such changes are made on the gear grinder and do not require shaving tooling. Similarly, manufacturers now rough-hob gear blanks, heat treat them, then grind them to specification on new CNC or computer-controlled gear grinders. Shaving is no longer required for production either.

Benefits of Ground vs. Cut Gears

As an alternative to cut gear sets, ground gears offer many benefits. These include:

- Uniform profile on all teeth of a specific gear and on all gears of the same design;
- Increased load capacity;
- Higher quality (up to AGMA class 15); and
- Elimination of the need for matched sets.

Grinding corrects spacing errors caused by prior machining and heat treatment. This improves gear set strength by allowing greater overlap ratios and evenly distributed tooth-to-tooth loading. Root radius grinding also improves the bending strength of gear and pinion teeth.

Noise reduction is achieved through the improved overlap ratio and tooth contact control. Tooth flank curvature in both profile and lengthwise direction may be accurately controlled to produce the low gear set motion errors required for quiet operation.

While conventional cut/hardened/lapped gear sets are not interchangeable, grinding produces more consistent tooth geometry, introducing the possibility of interchangeable gear members of a given design.

Finishing Techniques

Gears can be finished before or after hardening. When finishing is done before, distortion caused by heat treatment reduces the accuracy of the part. Machining adjustments can compensate for some of the anticipated distortion, but heat treating variables make highly accurate adjustments hard to achieve.

Grinding Methods: Spur and Helical Gears

Spur and helical gears are ground by three basic methods: single index generation, continuous generation or form grinding.

With the index generating method, the disc-shaped grinding wheel generates a single tooth slot by feeding the wheel through the slot in a series of passes. Each pass is preceded by a small radial infeed. The wheel grinds a single flank on one tooth or both flanks of adjacent teeth, then indexes to the next tooth space.

Continuous generating uses a grinding wheel in the form of a threaded worm or hob. As in the single index procedure, the grinding wheel is fed in the direction of the axis of rotation of the gear for a number of passes.

During form grinding, a shaped abrasive wheel passes between two teeth, grinding the entire surface of the adjacent tooth flanks. The gear is then indexed to the next tooth space.

Form grinding and index generating grinding are suitable for producing batch quantities of gears with diametral pitches generally coarser than 3 or as fine as 15. The continuous involute generating method is appropriate for large volume production and jobbing of gears up to 3 diametral pitch.

New Methods for Bevel and Hypoid Gears

New CNC equipment has changed the way bevel gears are made as well, replacing the traditional cut/harden/lap approach with cut/harden/grind for Formate® gear sets. When straight cup grinding on the machine, gear or pinion slots are generated by a relative motion between the wheel and the workpiece. This motion causes the wheel to function as a single tooth of an imaginary generating gear that mates with the workpiece. When the wheel axis rotates about the cradle axis, the generating gear tooth rolls with the workpiece to produce the desired tooth flank surface.

Generating Grinding Machines for Spur and Helical Gears

Depending on the type of wheel used, generating grinding machines fall into three categories: threaded, saucer or conical. Threaded wheel machines—made by Reishauer and Gleason (the new Gleason TAG 400)—are fast, high-precision units designed to accommodate external spur or helical gears up to 30" in diameter with helix angles up to 45°. For helical gears, pitch and helix angle determine the maximum face width.

Threaded wheel grinders are capable of producing tooth profile, spacing and lead within .00020", with excellent surface finish. Though CBN wheels have been successfully used in some thread worm applications, good results can generally be achieved with a good grinding oil and a vitrified aluminum oxide wheel.

Maag manufactures saucer wheel grinders; Niles and Höfler machines are designed for extremely large gears. These types of machines are suitable for grinding external spur and helical gears. Depending on the model, capacities range up to 142" in diameter. The diametral pitch varies from 6 DP to 25 DP on the smallest machine and from 1 DP to 9 DP on the largest.

Saucer wheel grinding supports topological modification, a technique that allows for the machining of an infinite variety of tooth forms. The tradeoff, however, is a slower cycle time. With saucer-type grinding, wheels may be set parallel to each other or at an angle of up to 100°. Vitrified aluminum oxide wheels are most commonly used. Grinding is done without coolants or oils, and dressing, done through wheel compensation, is accomplished with single-point diamonds.

Conical grinders have not been manufactured in great numbers since World War II. Large numbers of them, however, are still being used in the USA. Made by Reishauer, Höfler, Niles, Liebherr, Pfauter-Kapp and Gleason, these machines are typically designed to grind only external spur and helical gears.

Form Grinding Machines for Spur and Helical Gears

Form grinders are manufactured by Kapp, Leibherr, Okamoto, Gleason, National Broach and Orion (USA). These machines grind external and internal spur and helical gears up to 36" in diameter, with diametral pitch capacities from 64 to 2.

More flexible than their generating counterparts, computer-controlled form grinders lessen the hazards of surface tempering and require less setup time. Limited only by the type of forms that can be ground on the wheel, they're also more accurate, carrying out exact repetitions of the selected optimum grinding cycle. Wheel truing, profiling and dressing—also software controlled—can be done with diamond disks, single-point diamonds or diamond preformed dressing rolls.

Form grinding is most cost-effective when wheel wear and downtime are minimized. If production volumes justify it, the best ways to achieve those ends include the use of diamond dressing rolls, no-wear/no-dress plated CBN wheels and creep-feed grinding processes, which reduce wheel wear.

Grinding Machines for Bevel and Hypoid Gears

Bevel and hypoid gear grinders use cup-shaped wheels. Straight wheels are used to generate pinion or gear members. The Gleason flared cup process may be used to finish Formate gears. The Phoenix grinder implements this motion

Fig. 1 — Seeded gel threaded and cup-type grinding wheels used for grinding final drive helical and hypoid bevel gears.

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with coordinated X-, Y-, Z-, B- and A-axis movements which are similar to generating motions.

Breakthrough Bonds and Abrasives

Though grinding equipment is expensive, advances in grinding wheel technology enable faster speeds and feeds, which shorten cycle time and reduce costs. Such advances include the development of CBN, Seeded Gel (SG®) and TARGA™ abrasive wheels.

Cubic Boron Nitride (CBN)

The hardness of CBN (4700 Knoop scale) is second only to diamond. Classified as a superabrasive, CBN wears more slowly than conventional abrasives. It also conducts heat away from the ground surface, reducing thermal damage.

In recent years, manufacturers of precision gears (AGMA classes 12 to 14) have adopted CBN finishing for military and aircraft applications.

Though the initial cost of CBN is much higher than that of conventional abrasives, CBN finishing has been found to cut production time, improve quality and reduce manufacturing costs by as much as 80%.

Seeded Gel (SG) Aluminum Oxide

SG abrasives are manufactured by a sintering process that results in abrasive grits consisting of thousands of submicron-size aluminum oxide crystals. During dressing or self-sharpening, the grains shed these very small particles. The results are higher sharpness and lower total wear than for conventional abrasives. Due to more uniform microstructure and increased chemical purity, SG is also harder (2100, Knoop scale) than conventional aluminum oxide.

Since SG grains fracture by shedding submicron particles, wear flats do not develop at the working surface of the grinding wheel. Instead, sharp, relieved cutting edges are produced. As a result, seeded gel abrasives are sharper than conventional aluminum oxide.

Because of the increased hardness and the structure of the SG grains, SG generally wears longer than conventional aluminum oxide. As small particles break away from the grain due to grinding forces, only small portions of the total grain volume are lost.

SG functions best when aggressive metal removal rates are required and/or where the wheel wear conditions are severe. SG may also be the best abrasive choice for hard-to-grind materials, such as Waspalloy or other stainless steel alloys typically used in aerospace applications.

The recommended abrasive for flared cup grinding on Gleason machines, SG may offer improved performance over conventional abrasives for generated pinions and gears as well.

In use, self-sharpening SG has been found to increase the number of parts ground between dressings and to reduce wheel dressing by up to 80%. When tested, SG wheels finished 40 automotive gears per dress vs. 12 gears with conventional aluminum oxide wheels.

TARGA Abrasives— The Next Generation of SG

TG abrasives, which perform in a more focused environment, feature a grain that is processed into elongated shapes with an aspect ratio dependent on both the type of abrasive product and the grinding application. The shape of TARGA abrasives establishes slightly more porosity than is shown in the typical specifications, a fact even more evident in higher structure TARGA wheels.

TARGA users find lower power draw produces higher unit forces per grain in higher structure wheels. TARGA users will gain benefits from the grain shape which lends itself to naturally increased porosity. This porosity increases unit pressure on the grain, which yields lower power draw with the benefit of achieving near superabrasive results in applications of creep-feed grinding of aerospace alloys.

Like SG wheels, TARGA abrasives are considered an alternative to the more costly vitrified

Important Grinding Wheel Characteristics

Wheels are classified according to a standard marking system (see Fig.2) that specifies the following characteristics: abrasive type; grain or grit size; grade; structure; bond; wheel type; and bond type.

Manufacturers' abrasive type, the first element in the marking system, specifies the class of a given abrasive. Norton, for example, offers several classes of aluminum oxide which differ in purity, crystal structure and friability.

Grain or grit size indicates the degree to which abrasive grains are rough or fine. In this system, the abrasive size increases as the grit size becomes finer. Wheel grade or hardness refers to the bond strength, or the force required to break the grain from the wheel. In this case, alphabetic letters are used to designate grades from soft to hard.

The structure of a grinding wheel refers to the spacing of the abrasive grains in the bond matrix. Grinding wheel structures from dense to open (low to high porosity) are indicated by increasing structure number.

The bond system is normally a function of the selected abrasive type, bond grade and structure; not an end-user variable. Wheel manufacturers have their own designations for bond systems, and must therefore be consulted for bond system recommendations and information.

bonded CBN wheels for most gear grinding applications using conventional grinding equipment.

SG Dressing Characteristics

SG abrasive is harder than conventional aluminum oxide (2150 Knoop hardness versus 1850 Knoop hardness). Consequently, SG may wear low-quality diamond dressing tools faster than conventional abrasives. SG may contribute to the erosion of the bond matrix of some diamond rolls. Modifications to the diamond roll bond matrix of some diamond rolls can prevent this, as well as modify dressing practices. When purchasing diamond rolls, specify that SG wheels are being utilized.

On the positive side, SG likes to be dressed less for better performance, which increases the life of the dressing tool. For effective dressing with SG, consider the following points:

• Use "A" or "B" quality natural diamonds

• Reduce dresser infeed rates. The rule of thumb is to cut infeed depth by 50%, though more is not uncommon.

Effective Dressing—SG and Conventional Abrasives: Single Point Diamond and Diamond Rolls

The dressing rate used has a significant impact on cutting ability, part accuracy and finish. Finely dressed wheels will hold their form, producing good finish and accuracy. However, they may load too quickly and cause burn or chatter. By increasing dresser rates and using a rapid traverse rate, a more open wheel with sharper cutting action will be gained.

The rate at which the single point diamond travels across the wheel face is known as dress lead. Dress lead is the distance the diamond travels for every rotation of the wheel—much the same as the thread on a screw.

Typical lead values are:

• Form grinding .0005–.001" per rev.
• General-purpose grinding .002–.003" per rev.
• Fast cutting/heavy stock .004–.005" per rev.

To determine the rate of diamond traverse for a desired lead, multiply the lead in inches by the RPM of the wheel. For example:

4000 RPM x .002"/rev. = 8 IPM dress rate.

Typical diamond infeed on roughing operations is .0005–.001" per pass. Finish operations require .0001–.0005" per pass.

A very fine finish can be obtained by making the final diamond pass with no infeed.

Diamond roll dressing is implemented for one or more of the following reasons: intricate form profiles; consistent accuracy of size and form; control of grinding wheel sharpness; control of workpiece surface finish; and production economics.

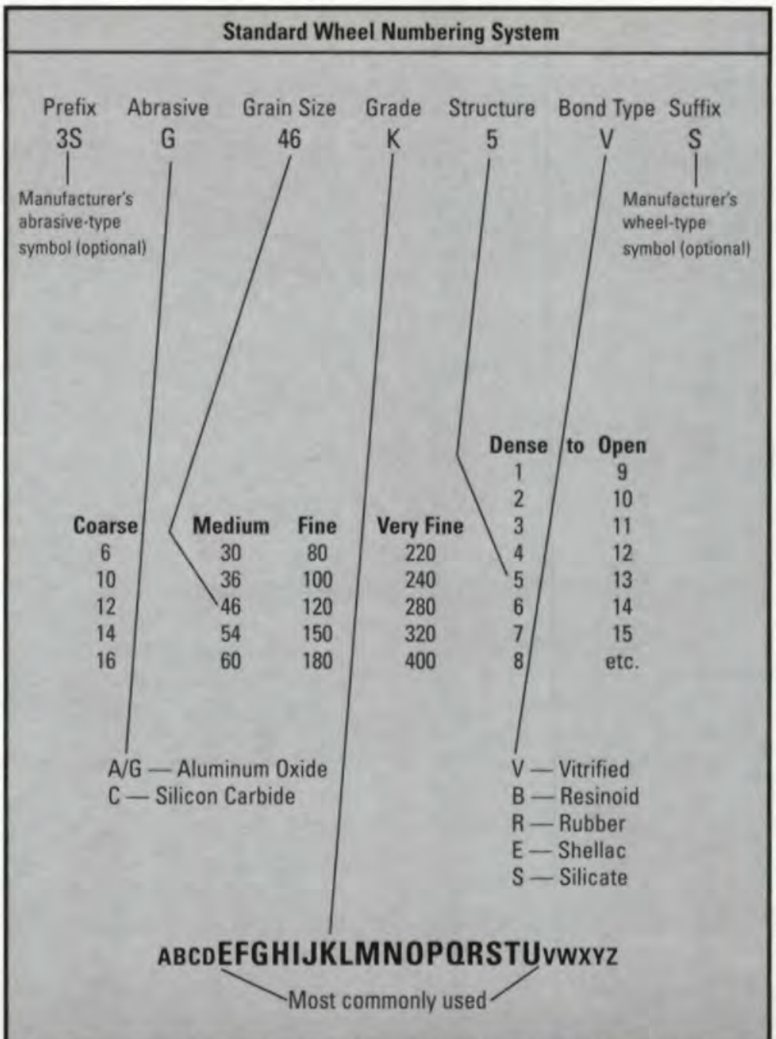

Fig. 2 — The marking system used by most manufacturers to identify important grinding wheel characteristics.

Courtesy of The Gleason Works.

Recommendations for speed ratio, rotation and materials are as follows:

• Maintain a speed ratio between .5 and .8;

• Maintain unidirectional rotation at the point of contact for most gear grinding;

• Use reverse-plated rather than bonded diamond rolls for superior durability and maximum diamond exposure.

To maximize the cost-effectiveness and efficiency of rotary diamond dressing devices, select a drive motor unit that complements the efficiency and accuracy of the diamond roll. Keep the following points in mind when making the selection:

• Older hydraulic motors, which generate a great deal of heat, may seriously affect the accuracy of axial run-out of the diamond roll as well as axial positioning.

• Air drives cause problems when running the dressing rolls at close to synchronous speed with the grinding wheel. At 0.8 to 0.9 ratio, the dresser has to act more like a brake to keep the dresser from rotating at wheel speed.

• Choose electrical drive motors that prevent the dresser from rotating at wheel speed and main-

Table I

Recommended Wheels—Threaded Generating Grinding Machines		
Results:		
Good	38A 120/180 HIJ VBE	
Better	3SG 80/120 IVS G12USP	
Best	3TG 120/3 GB VCFIII	
Recommended Wheels—Saucer Generate Grinders		
Results:		
Good	32A 46/80 K/L UBE or 38A 80/5 H/J VBE	
Better	3SG 80 G12 VSP	
Best	3TG 120/3 GB VCFIII	
Recommended Wheels—Bevel and Hypoid Machines		
Results:		
Good	38A 60/80 J VBE	
Better	55G 60/80 I/J VS	
Best	5TG 120/2 I/J VH	
Recommended Wheels—Niles and Höfler Machines (large gears)		
Results:		
Good	32A 60/5 G25-H16 VCFIII	
Better	3GP 54 GVSP	
Best	5TG 120/2 GB-HB VCFIII	
Recommended Aluminum Oxide Wheels—Form Gear Grinders		
Results:		
Good	32A 60-80/S G-J VBE-VBEP	
Better	3SG 100 G-I VS-VSP	
Best	3TG 120/4 GB VCFIII	
Recommended CBN Wheels—Form Gear Grinders		
CB 180-220 plated/nickel bond or CB 180 MNV x222 C1/8 vitrified bond		
Recommended Wheels—Form Grinding From a Solid		
Results:		
Good	SG 54-80 J-L VS	
Better	SG 54-80 J-L VH	
Best	5TG 120/ J-L VH	

tain a fixed set value of dresser RPM (2 kw or 2.65 hp minimum is recommended). Mechanical isolation is also imperative to eliminate vibrations from couplings and the drive motor itself to the roll.

Making the Right Choices

Grinding wheel selection directly influences at least four major performance factors:

1. Quality of the ground part, including flank form repeatability, tooth spacing, surface damage caused by burning and surface texture;

2. Floor-to-floor time, including wheel dressing/conditioning time and grinding time;

3. Abrasive tooling costs;

4. Flexibility to change the wheel profile for current and new jobs.

For these reasons, it is important to understand wheel and abrasive properties that are most critical to grinding performance and to seek further information from wheel and/or abrasive manufacturers in the event of any questions.

Apart from standard aluminum oxide wheels, there are two choices, each with its positive attributes:

SG and TARGA

- Higher metal removal rate capability than conventional abrasives, but lower than superabrasives.
- Increased sharpness to reduce tendency for burning.
- Longer lasting and better form holding capability than conventional aluminum oxide.
- Flexible, but very repeatable profile shapes.
- Self-sharpens properly with relatively high grinding forces.

Plated CBN

- Wheel dressing not required; reduces cycle time and saves expense of dressing tool.
- High metal removal rates because of hardness and toughness of CBN.
- Low tendency for burning—coolant application is easily optimized because wheel size and shape does not change through dressing.
- Thermal transfer properties of wheel materials (CBN, nickel bond, steel core) reduce tendency to burn.
- Compressive residual stresses left in workpiece surface layer increase strength.

In Conclusion

CBN abrasives offer excellent thermoconductivity and a cooler grinding process that helps to reduce tensile stresses and increase compressive stresses. As mentioned in related articles (including Wilfried König's "CBN Gear Grinding—A Way to Higher Load Capacity?" *Gear Technology*, Nov/Dec, 1993), the performance characteristics of CBN abrasives are the subject of much debate. This is particularly true in light of recent developments related to SG and TG abrasives. Like CBN, SG and TG abrasives have been proven to reduce tensile stresses and increase compressive stresses as well.

Recently, some manufacturers have found that the new abrasives have provided the required level of compressive stresses to enhance the performance level of their gears.

As this article is written, new technologies in abrasives and gear manufacturing equipment are being developed. These developments will provide gear manufacturers with more options, more choices and improved ways to produce higher quality gears with greater efficiency. ○

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