Grinding of Spur and Helical Gears

Dr. Suren B. Rao
National Science Foundation
Washington, D.C.

Grinding is a technique of finish-machining, utilizing an abrasive wheel. The rotating abrasive wheel, which is generally of special shape or form, when made to bear against a cylindrical-shaped workpiece, under a set of specific geometrical relationships, will produce a precision spur or helical gear. In most instances the workpiece will already have gear teeth cut on it by a primary process, such as hobbing or shaping. There are essentially two techniques for grinding gears: form and generation. The basic principles of these techniques, with their advantages and disadvantages, are presented in this section.

A general introduction to the basic principles of the grinding process, however, precedes the discussion of gear grinding techniques. This is based on the belief that the discussion of the grinding process, in combination with the description of the gear grinding techniques, would constitute a more complete treatise on gear grinding.

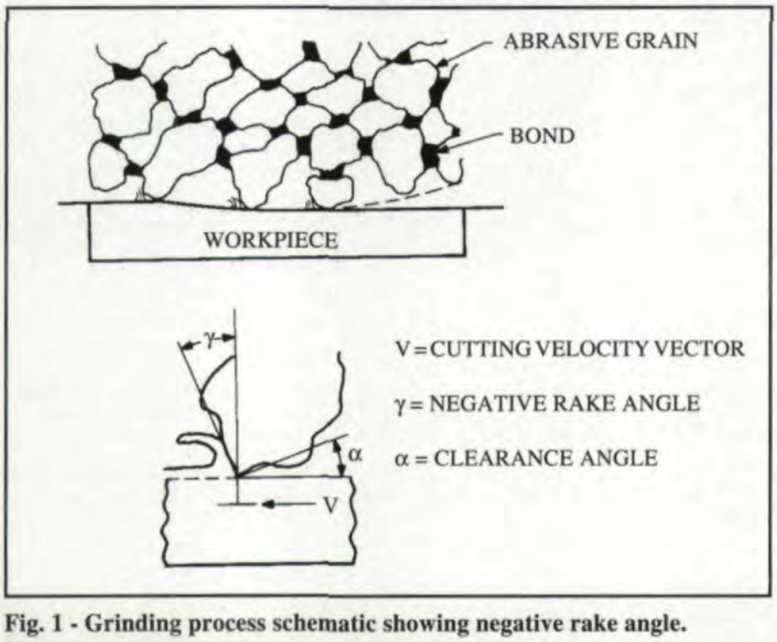

Fig. 1 - Grinding process schematic showing negative rake angle.

Reasons For Grinding

There are two primary reasons for grinding gears. In spite of several attempts to the contrary, it still remains one of the most viable techniques of machining gears once they are in a hardened state (50 Rc and above). Also, the process, in combination with highly accurate machines, is capable of gear manufacturing accuracy unmatched by other manufacturing techniques. AGMA gear quality 12 and 13 are common, and AGMA gear quality 14 and 15 are not unusual. With the advent of cubic boron nitride (CBN), grinding has been tried, with some success, as a primary operation on hardened material instead of hobbing or shaping before heat treatment (sometimes referred to as "direct grinding"). Obviously this is of greatest consequence only if a gear is being made from through-hardened material, a process that is not very common. It is much more common for gears to be made of case-hardened material where the economics of grinding from the solid are not as beneficial.

Gear grinding is an expensive operation and has to be justified on the basis of required gear quality in the hardened condition. The basic principles of grinding are now presented.

Grinding Process Mechanics and Process Parameters

Grinding is a metal cutting process not unlike single- or multi-point machining, such as turning, milling, hobbing, etc., but with some major dissimilarities. Grinding is characterized by the fact that the cutting tool, in this case the grinding wheel, consists of a very large number of randomly oriented cutting edges machining small amounts of material, thus resulting in extremely fine chip thicknesses. While chip thicknesses of 20 μm (0.0008") or more are common in operations like turning, and chip thicknesses of 8 μm (0.0003") are common in operations like milling, chip thicknesses of less than 1 μm (0.00004") are the norm in grinding.

Though the abrasive particles in the grinding wheel are randomly oriented, by virtue of their shape, they generally present a large negative rake angle to the cutting velocity vector as seen in Fig. 1. Negative rake angles always result in higher cutting forces than do positive rake angles. Also, small chip thicknesses result in higher specific cutting forces, where *specific cutting force* is defined as the force required to cut a unit area of chip cross section (kgf/mm^2 or $lbf./in^2$). The combination of negative rake and low chip thickness gives rise to high specific power requirements in grinding. Specific power is defined as power required to machine unit quantity of material in unit time ($hp/mm^3/min$ or $hp/in.^3/min$). This is not only indicative of the low efficiency of the grinding process, but also its high susceptibility to burning damage, as all the power consumed by the operation is converted into heat. The small chip thickness, however, also enables the generation of a high-quality surface and tight dimensional tolerances that make this process critical to the manufacture of high-precision gears and components.

The combination of large negative rake angle on the abrasive grain and small chip thickness also results in cutting process stiffnesses in grinding that are almost several times the cutting process stiffnesses in other machining processes, such as turning and milling. *Cutting process stiffness* here is defined as the force per unit chip thickness and is generally expressed in kgf/mm^2 ($lbf/in.^2$) of chip thickness. Since the rate of reproducibility of error due to a machining process is given by the formula:

$$\delta = \frac{\mu}{1 + \mu}$$

where δ is the rate of reproducibility and μ is expressed by the formula:

$$\mu = \frac{R}{K}$$

where K is the stiffness of the machine tool and R is the cutting process stiffness.

In a typical turning operation K is several times R, and δ typically computes to less than 0.25. This signifies that only 25% of the initial work piece error will remain after the first turning pass. In grinding, however, since R is extremely large compared with K, values of $\delta = 0.95$ are not uncommon. This signifies that in grinding almost 95% of the initial work piece error may remain after the first grinding pass. It is obvious from this discussion that careful execution of all previous processes to ensure a good preground gear is essential to an economic and successful grinding operation.

Wear of the grinding wheel is an essential part of the process. As the sharp cutting edges of the abrasives wear out, cutting forces on that particular abrasive increase until either the grain fractures reveal new sharp cutting edges or the abrasive is pulled out of the bond and a new abrasive grain is exposed. In essence, if the process were in perfect harmony, the grinding wheel would be self-sharpening. But even though wheel wear is an accepted phenomenon, the rate at which it occurs is critical. For wheel wear results, not only in wheel replacement, but also in other nonproductive wheel preparatory operations, such as trueing, dressing, and profiling. Therefore, the ratio of work material removed to volume of wheel lost, also called the G ratio, is a measure of grinding efficiency. G ratios can range from less than one to several hundred, depending on these variables.

One other distinguishing feature of the grinding process is the fractional amount of time the abrasive grain is actually creating a chip, in comparison with the total time this grain is in contact with the work piece material. Three distinct phenomena have been recognized as occurring as the abrasive grain comes in contact with and leaves contact with the work surface. These three regions have been defined as rubbing, plowing, and cutting, and the actual cutting or chip formation may be occurring for only about 30% of the time the abrasive and the workpiece are in contact. The force at which the transition occurs from rubbing and plowing to cutting is called the *threshold force*. When the mechanisms holding the grinding wheel and the work exert a force in excess of this threshold force, grinding and metal removal will occur.

Finally, here is a word about spark-out. As a grinding process proceeds with the rotating grinding wheel being fed into the work material, cutting forces are generated. These cutting forces cause the electromechanical structure that holds

Dr. Suren B. Rao
is currently the Director of the Manufacturing Machines and Equipment Program in the Division of Design and Manufacturing Systems at the National Science Foundation. He has a doctorate from the University of Wisconsin. He also studied at McMaster University and at Bangalore University, India.

the grinding wheel and the workpiece to deflect away from each other. At a certain instant in the process, the infeed of the wheel and/or the workpiece is stopped, resulting in a reduction of the cutting forces. This causes the strain energy stored in the structure to overcome the deflection and return the system to a state of equilibrium. As this happens, the wheel and workpiece move into each other and continue to grind as the forces decay to the threshold force level, after which no more grinding occurs. This part of the grinding process, where no infeed occurs but grinding continues, is called *spark-out*. The time taken to complete spark-out is a measure of the stiffness of the structure of the machine tool-tool-workpiece system. In general, some amount of spark-out in a grind cycle will improve work piece quality.

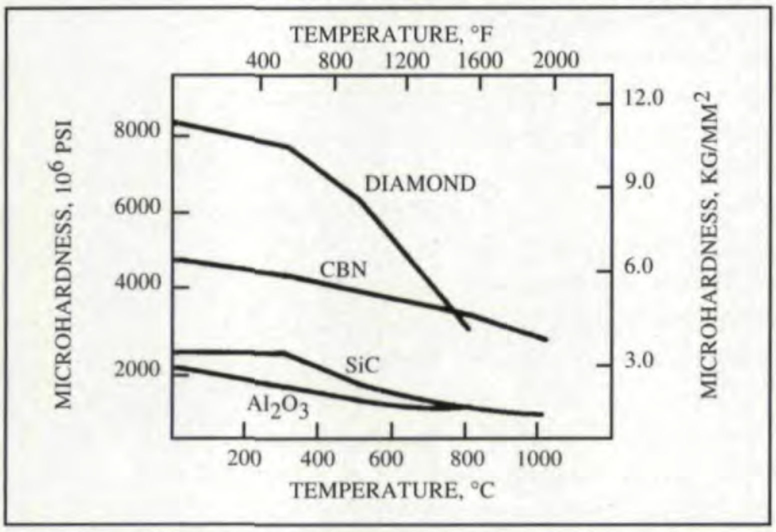

Fig. 2 - Comparative hardness of abrasives at elevated temperatures.

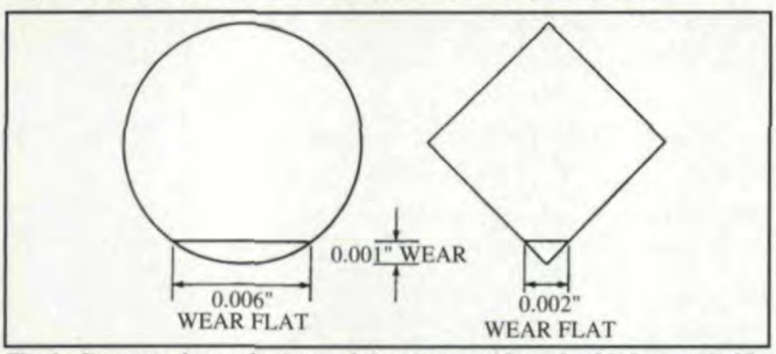

Fig. 3 - Comparative grain shape of aluminum oxide and cubic boron nitride.

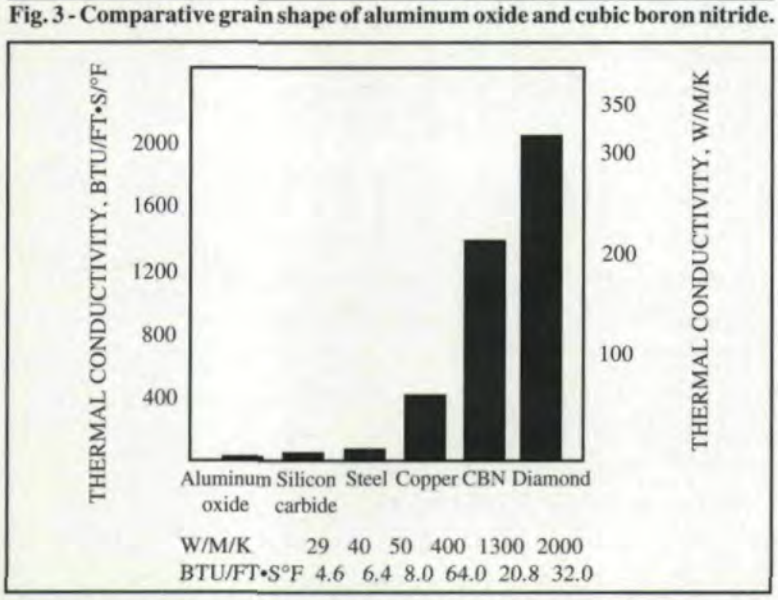

Fig. 4 - Comparative thermal conductivity of abrasives and other materials.

Abrasives

Though aluminum oxide (Al_2O_3), silicon carbide (SiC), diamond (C), and cubic boron nitride (CBN) are generally considered in the category of abrasives where grinding is concerned; only aluminum oxide and cubic boron nitride are discussed further. This is because in gear grinding we are usually dealing with ferrous alloys, and diamond and silicon carbide tend to perform poorly when grinding steel. High wear rates of the diamond or silicon carbide abrasive when grinding may be due to interatomic diffusion of the carbon atoms present in these two abrasives, since steel is characterized as "carbon hungry" at the elevated temperatures that are encountered during grinding.

The characteristics of aluminum oxide and cubic boron nitride that impact their performance as abrasives are now presented in a comparative manner. It is obvious from the following that cubic boron nitride is a considerably superior abrasive, though more expensive than aluminum oxide.

Hardness. Fig. 2 shows a comparative plot of diamond, cubic boron nitride, silicon carbide, and aluminum oxide hardness at elevated temperatures. It is obvious that cubic boron nitride is several times harder that aluminum oxide and even harder than diamond at temperatures higher than 1472°F (800°C). The chemical inertness of cubic boron nitride is also of significance, since any chemical affinity to iron would result in increased wear rates.

Grain Shape. When comparing grain shapes of aluminum oxide and cubic boron nitride, the former is known to have a more pronounced spherical form, while the later has a block form. For a given amount of crystal wear, a spherical form exhibits a larger wear area than does a block form (Fig. 3). Tendency to burning has been related to wear flat area, indicating that higher degrees of burning and surface damage are possible with aluminum oxide than with cubic boron nitride.

Thermal Conductivity. Fig. 4 shows a comparison of thermal conductivity of the various abrasives and some common metals. Though diamond has the highest thermal conductivity, cubic boron nitride is not far behind and considerably higher than aluminum oxide. The high thermal conductivity of cubic boron nitride allows more of the heat generated at the abrasive-work material interface to flow into the abrasive and into the wheel than into the work piece, resulting in reduced tendency for surface damage. It must be remembered, however, that it is possible to produce thermal damage with cubic boron nitride. The combination of high thermal conductivity and lower wear flat area owing to grain shape allows for much higher metal removal rates to be achieved and higher spindle powers to be utilized before thermal damage can occur. The impact of a grinding abrasive on the work piece will generally induce a compressive stress on the work surface. However, the localized heating and subsequent cooling that is more predominant when grinding with aluminum oxide overcomes the compressive stress due to mechanical impact, and the residual stresses in the uppermost layers of the work piece are highly tensile. The absence of this heating when grinding with cubic boron nitride results in residual stress that is a compressive on the work surface. Fig. 5 shows typical residual stress profiles produced by plunge grinding with the two abrasives. Since tensile stresses are accompanied by lowered fatigue life, clearly grinding with CBN offers distinctive advantages. The only drawbacks to the application of cubic boron nitride are its costs and the need for stiffer, higher-powered machine tools to fully utilize the advantages that cubic boron nitride has to offer.

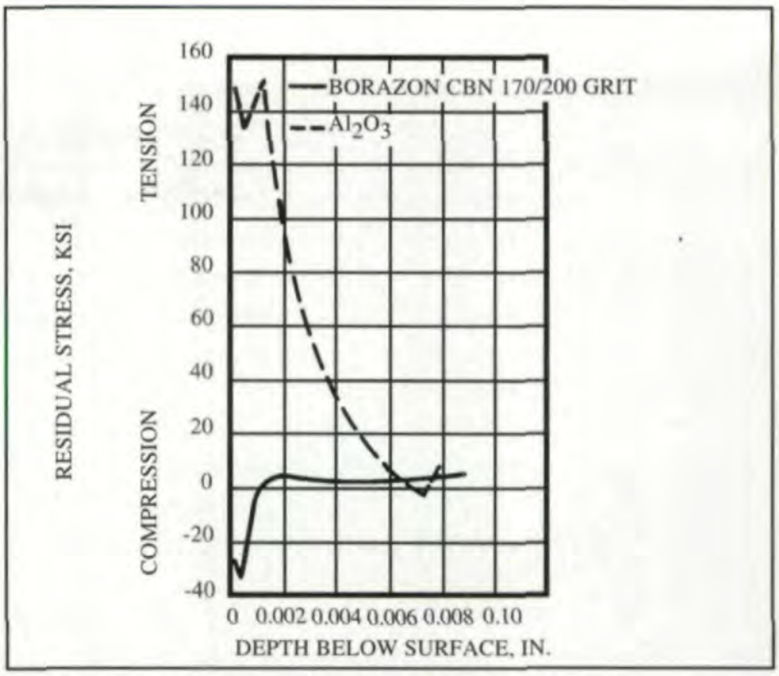

Fig. 5 - Comparative values of residual stress distribution.

Grinding Wheels

Grinding wheels and their properties are only briefly discussed here, as a considerable amount of literature is in existence, especially from wheel manufacturers, that covers this in detail. All grinding wheels, except electroplated wheels, consist of an abrasive held in a bond. The physical size of the abrasive is a major determining factor in abrasive grain concentration and in the number of cutting edges engaged in the process of grinding at any given instant in time; that is, the larger the abrasive size, the fewer the number of abrasives and cutting edges, and vice versa. This in turn impacts the chip thickness as grinding proceeds and, consequently, the surface finish that is obtainable. In general, coarse abrasive grain sizes, also called grit sizes, result in rougher ground surfaces and finer grit sizes in lower surface roughness values. Surface roughness values of 0.4 μm (16 μin.) are generally possible with 60 grit size abrasives, and values better than 0.1 μm (4 μin.) are possible with abrasives of 200 grit size or finer.

Wheel hardness is another important characteristic of the wheel and is related to the amount of bond used in the manufacture of the wheel. A hard wheel has more bond, resulting in a greater abrasive retention ability. The abrasive will have to become considerably dull, in regard to its cutting edges, before sufficient forces are generated to tear it away. On the other hand, a soft wheel has less bond and consequently will lose its abrasive grains more readily. In general, soft wheels are used with hardened materials because the abrasive grain is known to dull rapidly when machining the hard materials, and fresh, sharp abrasives will be required to continue grinding without the occurrence of high temperatures and surface damage. On the other hand, hard wheels are generally used with soft materials, since the abrasive is expected to last longer, and abrasive grain retention is a property that is desired from an economic point of view.

Wheel structure is another important characteristic. An open structure allows greater chip clearance and is preferable in roughing operations where large quantities of material may be removed. Lack of sufficient space for chips would result in the loading of the wheel with subsequent burning of the work surface. However, open-structure wheels are also softer, because of the reduced amount of bond material.

Abrasive grain size is specified by the wire mesh size that will allow the abrasive to pass through. The smaller the number, the larger is the grain size. It must be remembered that the mesh size specified only indicates that grains larger than the specified value do not exist in the wheel, but smaller abrasive grain sizes do. In general, the grain size distribution can be assumed to follow a normal distribution. Wheel hardness or wheel grade is specified with a letter, with A being the softest and Z the hardest. Wheel structure is generally specified with a number, with 1 representing a close structure and 10 representing a very open structure.

It must be remembered that there are no absolute relationships between work piece and wheel characteristics. The aforementioned facts are only guidelines, and the exact choice of a wheel for a particular work material-grinding operation combination has to be arrived at on the basis of trial and experience.

Wheel Preparation. In most grinding operations where a dressable wheel is used, four distinct operations may be present, singly or in combination: 1) wheel trueing, 2) wheel dressing, 3) wheel profiling, and 4) wheel crushing. The purpose and procedure for these four operations are now discussed. The mechanism for accomplishing these operations is described later.

Wheel Trueing. In this operation wheel material is removed to eliminate wheel nonuniformities of shape and geometry due to wheel manufacture and mounting. The grinding wheel is mounted on its wheel holder, balanced, and then mounted on the machine spindle. Trueing is then carried out by the motion of a diamond tool in a direction along the axis of wheel rotation as the wheel is spinning at speeds close to or at grinding speeds. After all the nonuniformity is eliminated, the grinding wheel will need to be balanced again. Wheel trueing is generally necessary only when the wheel is mounted for the first time unless nonuniform wheel wear has occurred during the grinding operation. Trueing will reduce forced vibration problems due to nonuniform wheel shape and geometry, resulting in improved surface finish.

Wheel Dressing. This is required to eliminate the uppermost layer of dulled abrasive grains and expose the sharp, next layer of abrasive grains in the wheel to obtain efficient cutting. On a new wheel it becomes necessary to do this when the wheel is very hard and the bond material completely encloses the abrasive grain. For softer wheels the trueing operation is generally able to expose abrasive grains, and the first wheel contact with the work piece is sufficient to break down any bond material that may still be covering the abrasive. On harder wheels the bond material may need to be pushed back with a stick of silicon carbide or naturally occurring abrasives, such as corundum, etc. Too much bond removal is, however, detrimental, as abrasive grains would be unsupported and consequently lost easily, leading to loss of the wheel.

Dressing also clears the chip-loaded surface of the wheel, which may cause burning of this work piece. A loaded wheel, in combination with dull abrasive grains, will have a smooth, glazed surface. After dressing, the wheel surface will be rougher to the touch.

Wheel Profiling. In this operation the wheel is shaped to a specific profile in order to generate the required geometry on the work piece. This is of special significance in gear grinding, as the wheel is either representing a rack in some generating-grinding operations or the normal space between two adjacent teeth in form-grinding operations. Wheel trueing, dressing, and profiling can, however, be combined into one operation on a machine, especially if a medium or soft wheel is used. For hard wheels trueing and profiling can be combined, while initial dressing to push back the bond material is carried out as a separate operation.

Wheel Crushing. This is a technique used for rapidly removing wheel material to profile a wheel. A crushing roll, generally made of high-speed steel, with the required profile machined on it, is brought into contact under pressure with the grinding wheel, with no relative tangential velocity. Wheel speeds are generally reduced during this process to about one-fifth to one-tenth the actual grinding speeds.

Except for crushing and dressing of very hard wheels, all other wheel preparation operations are combined on most grinding machines. Profiling, trueing, and dressing can be done with a single-point diamond traversing the wheel surface in a specific relationship to generate the required profile. Where profile accuracy is influenced by the wear of the diamond point, a rotating diamond disk that represents many diamond points will improve results, since the diamond wear is distributed over many points. However, the disk should run true in axial and radial directions in order to maintain profiling accuracy. For much faster profiling, in combination with dressing and trueing, formed diamond rolls can be used. These rolls are, however, expensive, and sufficient part volume may be necessary to justify the investment. With a formed diamond roll, intermittent dressing when the grinding wheel is out of the cut or continuous dressing during the grinding operation are possible. Continuous dressing is especially effective for high-speed, creep-feed grinding, which is discussed later.

Grinding Processes

There are two distinct grinding processes used in gear grinding, as in most grinding operations. They are as follows:

Conventional Grinding. Fig. 6 illustrates the basic properties of this process, which is characterized by a wheel rotating at surface speeds of about 30 m/s (6,000 ft/min), infeeds of 0.01 to 0.050 mm (0.0004 to 0.0002 in.) and work velocities of 1.25m/min to 10m/min (50 to 400 in./min). The chips generated are short, due to the small arc of contact between an abrasive grain and workpiece in this process, and are easily disposed of. Wheel wear rates are generally high in this process, resulting in low to medium G ratios. This is because of repeated impacts between the edge of the work piece and the wheel due to the to-and-fro oscillations of the workpiece, for which reason this process is also sometimes referred to as pendulum grinding. Researchers have also found that in this mode of grinding, the average force per abrasive grain is high, further contributing to rapid wheel breakdown. Coolant is generally used, though dry grinding can be done if the amount of infeed is in the 0.0005-mm (0.0002-in") range when grinding hardened steel. This is due to the fact that metal removal rates are very small, with a small fraction of the wheel surface cutting at any given instant, with low power consumption and consequently low amounts of heat generation.

Creep-feed Grinding. Fig. 7 illustrates the basic properties of this process that are characterized by large infeeds into the work in excess of 0.5 mm (0.0125") and up to 10 mm (0.4"), depending on machine power and stiffness; but accompanied by much lower work velocities, which could be as low as 50 mm/min (2 in./min) and seldom exceeding 500 mm/min (20 in./min). Work velocity is inversely proportional to the infeed. Work velocities exceeding 250 mm/min (10 in./min) are generally accompanied by special dressing processes, such as continuous dressing, which enable the maintenance of a sharp, unclogged grinding wheel.

Since the infeeds are large, arc of contact between wheel and work is extremely large in comparison to conventional grinding. This results in each abrasive grain cutting a long chip. The wheel consequently has to have a very open structure to accommodate long chips.

The large arc of contact, which results in a large number of grains in simultaneous cutting action, requires high spindle power, which in turn results in large cutting forces and the generation of greater quanitites of heat than with conventional grinding. The machine tool has to have the necessary power and stiffness to withstand the larger forces, and a copious supply of

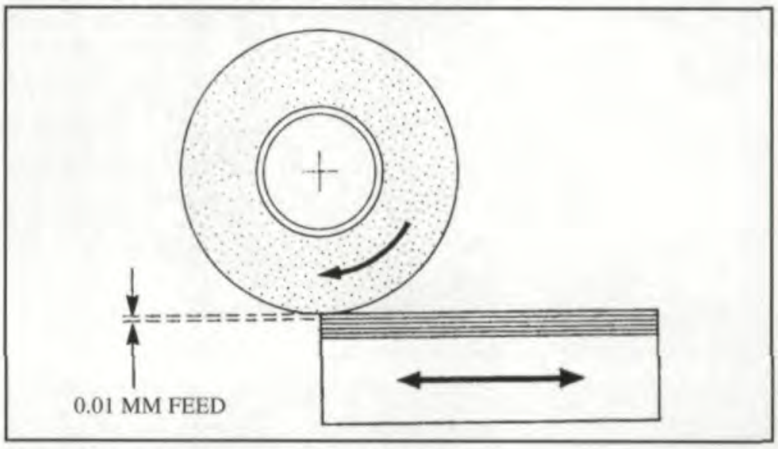

Fig. 6 - Conventional or pendulum grinding.

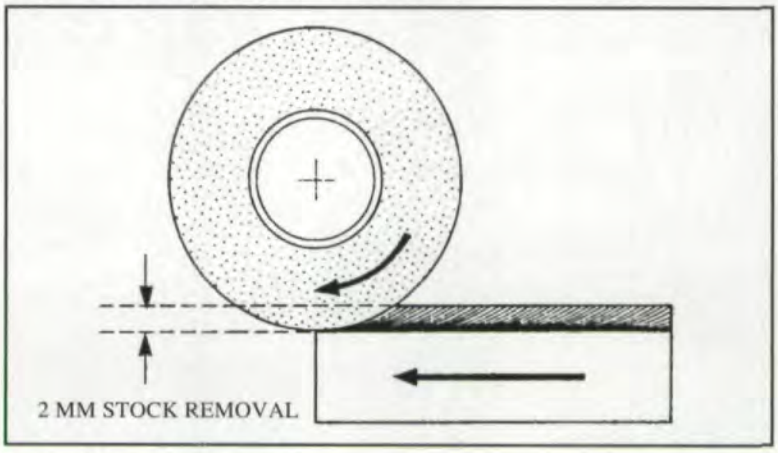

Fig. 7 - Creep-feed grinding.

well-directed coolant to carry away the heat generated in the process.

In spite of the larger power requirement, creep-feed grinding generally enjoys a higher G ratio than does conventional grinding when grinding similar materials. The lowered wheel wear is attributed to lower forces per abrasive in creep-feed grinding and also to the fact that in conventional grinding many wheel-work piece impacts are present as the work piece oscillates from side to side about the wheel.

Any means of eliminating the long chips produced in creep-feed grinding from loading the wheel will only improve the efficiency of the process. The use of high-pressure coolants to flush the wheel has been one techniques allowing higher work velocities. Another technique has been continuous dressing. Here the dressing roll, which may have the required form, is continuously fed into the wheel during the grinding process, with the grinding wheel being continuously fed into the work to compensate for reduction in wheel size. This continuous dressing keeps the wheel clean and sharp, allowing higher work velocities during creep-feed grinding. Experimental work where work velocities were in the 1m/min (40 in./min) range and higher have been reported.

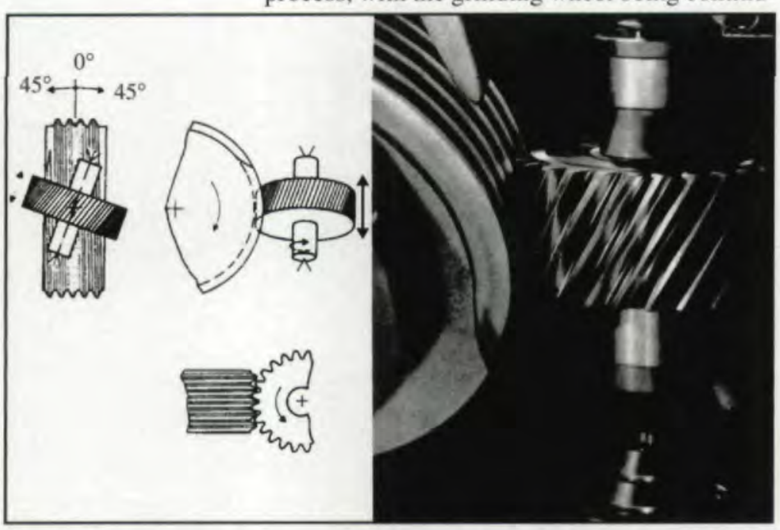

Fig. 8 - Kinematic representation of threaded wheel method.

Fig. 9 - Electronic threaded wheel-type gear grinder.

With this introduction to the various aspects of the grinding process, it is now possible to discuss gear grinding as practiced by the industry. The two most common techniques are form grinding and generating grinding. The techniques are now discussed in detail.

Generating Grinding

There are several basic techniques of generating grinding; each technique is associated with a specific machine-tool manufacturer. These distinct techniques are now presented.

Threaded Wheel Method. The basic machine motions that generate the gear in this method are kinematically illustrated in Fig. 8. The similarities of the mechanics of this technique to gear hobbing are very obvious, with the threaded grinding wheel replacing the hob. The ratio of work speed and wheel speed when grinding spur gears is a simple ratio of number of teeth on the gear and number of starts on the wheel. For helical gears this has compensated (differential indexed) for the traverse of the grinding wheel along the face width of the gear.

In order to be able to carry out the grinding process, the threaded grinding wheel, unlike the hob, has to achieve surface speed in excess of 25 m/s (5000 ft/min). The indexing mechanism has to be considerably more accurate in order to achieve the gear quality required in grinding. In the past, complex gear arrangements were normally used to obtain the simple and differential indexing requirements between the grinding wheel and work piece. However, *electronic gear boxes* (EGBs) are now commercially available to maintain the kinematic relationship. Fig. 9 shows a typical machine with an EGB for generating grinding.

The quality of the gear being ground is also significantly affected by the rack-type profile of the grinding wheel. It must first be introduced on a cylindrical wheel and then maintained through the grinding process as the wheel breaks down due to wear.

Introduction of the rack-type profile on a cylindrical wheel is done in two steps. A rough rack-type profile is crushed into the wheel using a steel crushing roll. This can then be finished by a variety of techniques using diamond tools, such as a single-point dresser or coated dressing disk. Profile modifications are introduced in this second step as required. With single-point dressing tools, profile modidifications are made using special cams. If coated disks are being used, the modifications are lapped into the disk by the machine manufacturer.

Saucer Wheels Method. This is another generating technique where two saucer-shaped wheels are used as shown in Fig. 10. The grinding surfaces of the two wheels represent the rack, and the involute profile is generated by the gear rolling relative to and in contact with the two grinding wheels. The wheels may be set parallel to each other or at an angle up to 10°. The work piece is reciprocated in the axial direction to provide the feed motion as two flanks of two different teeth are ground in one pass. At the end of the pass the entire gear is indexed using mechanical index heads so that two flanks of two or more teeth are then ground by the wheel. The depth of cut is determined by the infeed of the two grinding wheels toward each other.

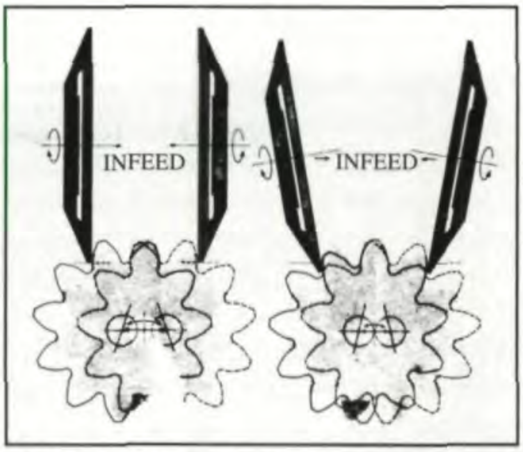

Fig. 10 - Saucer wheel method.

For spur gears, the axes of the grinding wheels are perpendicular to the axis of the gear and only simple motion, to simulate the rolling of the gear on the rack represented by the grinding wheel, is needed to generate the involute. This generating motion is produced by steel tapes fixed to a stationary tap stand, the other end of which is wound over a rolling block that is generally the same diameter as the base-circle diameter of the profile being ground. This is illustrated in Fig. 11. When grinding a helical gear, the rolling motion that is necessary to generate the involute has to be compensated for the helix angle as the grinding wheels move along the face width of the gear. This is accomplished by a helix guide mechanism attached to the tape stand that is used to generate the rolling motion. The helix guide is set to the base helix angle, and, as the gear moves along its axis, additional motion is imparted to it to produce the helix along with the involute.

On older machines of this type, changeover from one gear to another required the change of the rolling block for each change in base-circle diameter. On modern machines, mechanisms have been developed that allow a range of base-circle diameters that can be ground with the same rolling block.

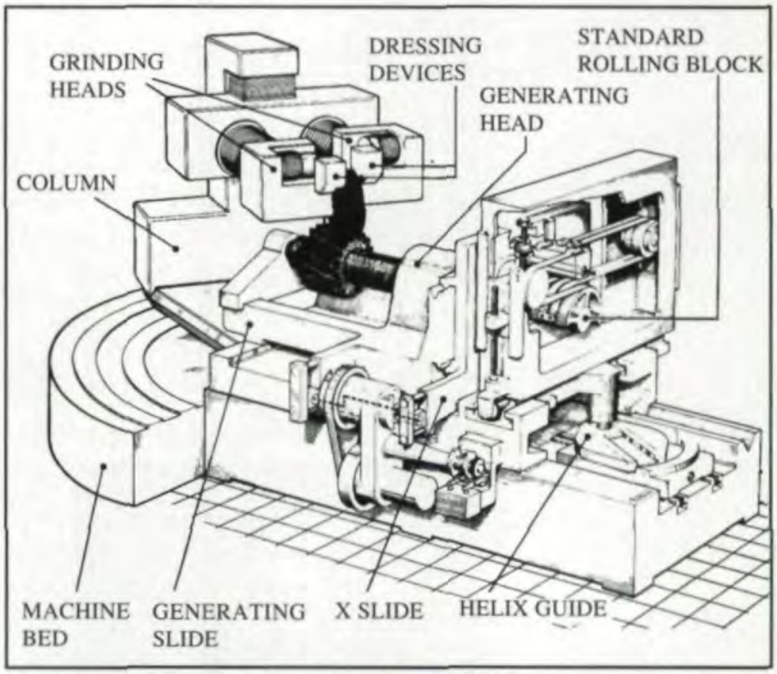

Fig. 11 - Typical saucer wheel grinder showing basic components.

The contact between the saucer-shaped wheel and the tooth flank is generally restricted to a very small area at any given time. This generally makes this technique of gear grinding time consuming and slow. However, it also enables point-by-point profile and lead modification along the flank of the tooth technique, termed *topological modification*. Consequently, the profile of the gear tooth can be different along the entire face width of the gear, a feature that none of the other gear grinding techniques, form or generation, can duplicate. Use of computers to control this topological grinding feature allows an infinite variety of tooth forms to be ground. It must be remembered, however, that this feature is at the price of slower cycle time, and tradeoffs have to be examined before a decision is made to use this technique. Also, at the present time, apart from a few gear tool applications, no other applications of topological grinding have been applied.

Vitrified aluminum oxide wheels are most commonly used in this method of gear grinding, and the grinding process is generally done "dry." Dressing is carried out with wheel compensation, using single-point diamonds. The purpose of dressing is to ensure that the rotating surface of the wheel represents a straight tooth of a generating rack. Single-layer, cubic boron nitride-plated wheels have also been tried, as they eliminate the need for dressing, and wheel life is high for reasons already explained in the text.

Conical Wheel Grinder. This is another version of generating grinding using a grinding

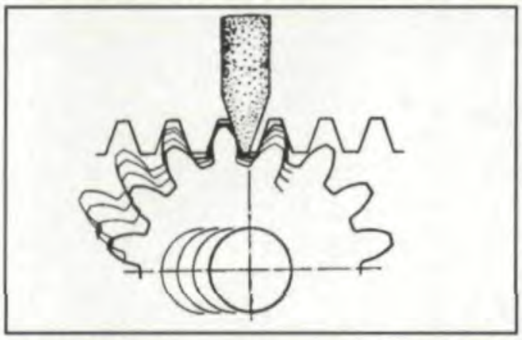

Fig. 12 - Basic concept of a conical wheel grinder.

Fig. 13 - Conical wheel grinder finishing a double-helical gear in one setup.

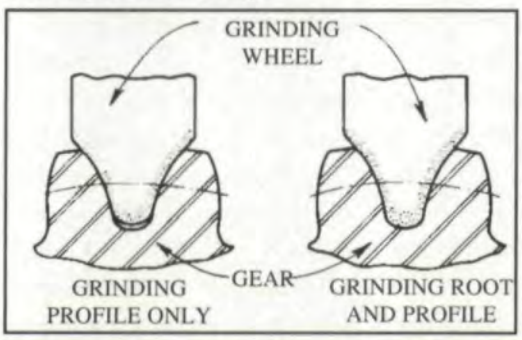

Fig. 14 - Basic concept of form gear grinding.

wheel that represents a single tooth of the rack, as shown in Fig. 12. The sides of the wheel correspond to the pressure angle of the gear being ground. The work gear rotates and translates linearly to generate the rolling action required to generate the involute profile.

The simultaneous rolling and linear motion is generally obtained by having a master gear with the same number of teeth mounted on the work spindle rolling on a stationary master rack. The master gear and rack must correspond to the gear being ground in terms of number of teeth, pressure angle, diametral pitch, etc. Electronic means of varying the base roll diameter to correspond to the gear being processed are, however, now available. In this process, as with the previously discussed saucer wheels method, two flanks of two different teeth are finished before the gear is indexed to grind two more flanks of two more teeth.

Helical gears can also be generated by this technique, though helical master gears and racks are required. If the wheel needs to be dressed, diamond points operating at the specific pressure angle are required. Since simple straight line forms need to be dressed, the dressing mechanism is relatively simple. Tooth profile modifications are produced by the modified grinding wheel. For lead modifications, the tool slide with the grinding wheel is radially advanced in synchronism with the stroking motion of the grinding slide, controlled through a tracer roll following the slope of the template. A moderate-sized conical wheel grinder, grinding a double helical gear is shown in Fig. 13.

Form Grinding

In this technique, the abrasive grinding wheel is profiled to represent the space between two adjacent teeth on a gear. The wheel is then passed through the space while grinding occurs on the two adjacent teeth flanks and the root, if required, as shown in Fig. 14. This is one of the primary advantages of form grinding in that various simple and compound root forms can be produced. Form grinding also enables the grinding of internal gears and external gears positioned against a shoulder.

When a spur gear is being ground, the wheel is simply moved along the axis of the gear. When a helical gear is required, the axial motion of the wheel is combined with a motion of the gear about its axis in order to produce the lead. The various axes of motion required to manufacture a gear on a horizontal axis grinder are illustrated in Fig. 15. The A axis provides the tooth-to-tooth index and, when interpolated with the X axis, generates the lead. The Y axis provides size control and, in combination with the X axis, provides lead modifications. The B axis allows the wheel to be set to the helix angle of the part. On a horizontal axis machine, two more axes are generally required to dress the profile on the grinding wheel. These are marked as the V and W axes.

An analysis of current gear grinding equipment indicates that form grinders are ahead of the generating machines in the application of computer control to gear grinding. In most generating machines it was found that only some aspects of the process were under computer control, while other aspects used mechanical control devices such as index plates, sine bars, or cams. However, contemporary form grinders appear to have completely abandoned mechanical devices in favor of computer control and appear to be doing as well or better than the older form-grinding machines. Also, computer control enables these form grinders to be more flexible and require less setup time than their generating counterparts.

Since the wheel profile is constant, modifying the lead by Y axis motion, which results in a change in center distance between the grinding wheel and the gear, will result in slight distortions to the profile. Lead modifications through change in the interpolation relationships between the A and X axes are also possible.

It is also important to note that, when grinding a helical gear, the normal tooth space that is represented by the grinding wheel has to be modified to account for the interference that occurs between the wheel and the helical groove, commonly termed *heel-toe action*. This heel-toe action is a function of the wheel diameter. Consequently, this has to be compensated for wheel diameter reduction during dressing to avoid errors in profiles.

In the past, mechanical devices such as sine bars, index plates, and cams were used to generate the helix, index, and profile, respectively. On modern computer-controlled machines, such as the one shown in Fig. 16, software generates and controls the relationships. Consequently, compensating for the involute as the wheel diameter

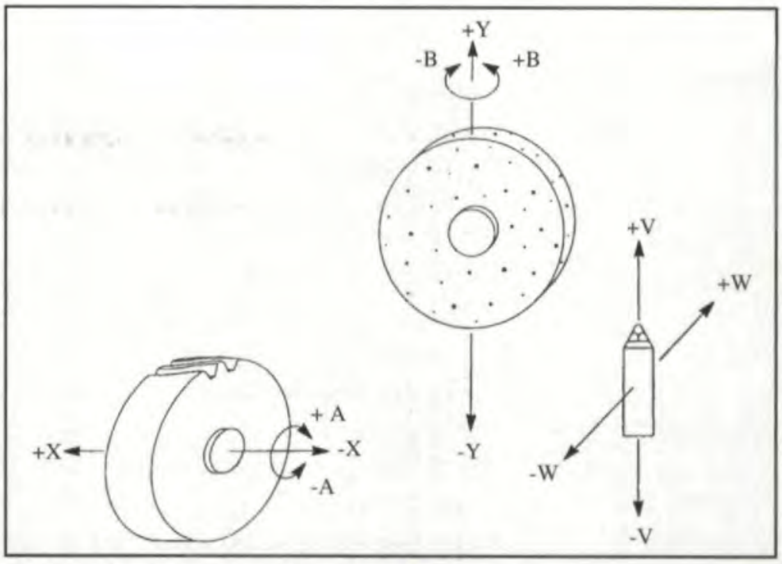

Fig. 15 - Axes of motion for form grinding.

Fig. 16 - CNC form gear grinder.

changes due to dressing can be done just as easily as speeding up the spindle is carried out for changes in wheel diameter in order to maintain constant wheel surface speeds. The only necessity is that the machine constitute a set of necessary accurate linear and rotary axes.

Wheeling trueing, profiling, and dressing are accomplished by the dressing mechanism. A diamond disk or single-point diamonds can be used. If production volumes can justify it, a diamond preformed dressing roll can be used to reduce dressing times and increase productivity. Alternatively, electroplated preformed cubic boron nitride wheels can be used, and dressing times can be completely eliminated (keeping in mind that preformed wheels may cost up to 100 times the cost of a dressable aluminum oxide wheel). Vitrified, dressable cubic boron nitride wheels can also be used. These need to be dressed, but not as often as aluminum oxide wheels, and are generally cheaper or about the same cost as a plated wheel.

The coordinates describing the profile that is used to control the dressing device are also generated by software. Two basic approaches are evident. One is a more fundamental approach based on solid geometry, where the grinding wheel and work piece are considered as two cylinders intersecting each other at a present distance and angle between the two axes. The shape of the intersecting surface on one of the cylinders, that is, the workpiece, is defined by the specified profile. Consequently the shape of the wheel surface can be computed. The profile may be an involute with modifications or a noninvolute if required. The other basic approach is heuristic or data-based in which profile coordinates corresponding to different pressure angles, modules (diametral pitch), base-circle diameters, and helix angles at P. D. are stored. Interpolated values of coordinates for other profiles can then be obtained. This approach is more limited in scope and may need a few trials to arrive at the right profile.

The ability of form grinding to produce noninvolute forms cannot be overstressed. Generating grinding is limited in this area as the gear profile is due to the rolling action of the work against the wheel. Form grinding is, on the other hand, limited only by the type of forms that can be generated on the wheel.

Since the accuracy of profile obtained in form grinding is directly impacted by wheel wear, any technique that could reduce wheel wear is obviously of benefit to the economics of the operation. Plated cubic boron nitride wheels, where wear of the wheel is almost nonexistent, represent one approach, providing it can be cost-justified. Creep-feed grinding, with its accompanying reductions in wheel wear, is another. In order to accommodate the creep-feed grinding process, current machines have been designed and built with high spindle power and high static stiffness to utilize the power, low table speeds, and large coolant flows. All these features have enabled the application of advanced processes to the technique of form gear grinding.

Cycle Time Estimates

These are essential in job shops for quoting purposes before a job of grinding a gear can be started. Keeping in mind the variety of gear grinding techniques available and the variety, of grinding processes that could be utilized, development of specific formulae to suit each process and technique was considered futile. Instead, a more general approach is now presented: an approach that can be modified to suit each technique or process as necessary.

The total time required to grind a gear is given by the expression:

Total time = grind cycle time + work handling time + setup time per gear.

Since the work handling time and setup time per gear are functions of sophistication and type of work-handling equipment and machine tool and the skill of the operator, further discussion is restrained to the grind cycle time only.

The *grind cycle time* is given by the generalized expression:

Grind cycle time = grind time + index time + wheel dress time + reset time.

Further, *grind time* is given by the expression:

$$\text{Grind time} = \frac{\text{gear face width} + \text{overtravel}}{\text{work traverse velocity}} \times \text{number of traverses} \times \text{number of gear teeth.}$$

Gear face width and number of teeth can be obtained from a part print; the amount of overtravel is a value necessary to clear the part for the purposes of indexing; and the work traverse velocity is a parameter that is dependent on a variety of factors, including the process and the type of machine tool being utilized. The number of traverses required for grinding is given by the formula

$$\text{Number of traverses} = \frac{\text{rough stock}}{\text{rough infeed}} + \frac{\text{semifinish stock}}{\text{semifinish infeed}} + \frac{\text{finish stock}}{\text{finish infeed}} + \text{number of spark-out traverses.}$$

All these aforementioned parameters are part- and process-dependent variables. The number of spark-out traverses is also dependent on the incoming quality of the gear, the required outgoing quality, and the stiffness of the machine tool being utilized. If the work traverse velocity in the expression for grind time changes during the rough, semifinish, finish, and spark-out, different grind times have to be calculated for each part of the process and summed to get the total grind time.

The *index time*, which does not exist in the case of generating grinding with a threaded wheel, is given by the expression:

The *index time* = time per index × number of gear teeth × number of index traverses.

The time per index, usually a few seconds, is dependent on the type of machine tool and the number of teeth and is a part-dependent parameter. The number of index traverses is based on the processes and can be computed from the expression:

Number of index traverses =

$$\frac{\text{number of rough traverses}}{\text{number of traverses/index}} + \frac{\text{number of semifinish traverses}}{\text{number of traverses/index}} + \ldots$$

This combination is due to the possibility of a number of traverses with grinding infeed on the same tooth before indexing, a technique that is used occasionally while roughing on a form grinder or generating grinder using saucer-shaped or conical grinding wheels. If the grinding process being used requires indexing after every traverse, then the number of index traverses is the same as the number of traverses.

The *dress time* is given by the expression:

Dress time = time per dress + number of dresses per gear.

In some types of generating grinding a number of gears may be finished between dresses and so a fractional value will have to be used for the parameter "number of dresses per gear." Also, the time per dress during roughing may be different from the time per dress during semifinishing, finishing, or spark-out, in which case the formula may have to be expanded to account for all these variables. Since a certain amount of time is usually required to bring the dressing mechanism into action at the start of each dressing cycle, this time should be added for a more accurate estimate of dress time.

The gear being ground, in almost all instances, is held between two elements on the machine during the grinding process, for example, a headstock and a tailstock for an external gear. Of the two, one is general the stiffer member, and consequently, it is preferable to grind against this member in what is generally characterized as unidirection grinding. (This is not to say that bidirectional grinding cannot be done, though this is restricted to roughing passes only.) The *reset time* is the idle time lost to reset the machine to do unidirectional grinding and given by the formula:

$$\text{Reset time} = \frac{\text{face width + overtravel}}{\text{wheel return speed}} \times \text{number of traverses} \times \text{number of gear teeth.}$$

The wheel return speed is generally the rapid traverse rate on the machine, though depending on the amount of travel, the table of the machine may never reach that speed. A lower rate should generally be used to account for acceleration and deceleration. If a combination of bidirectional and unidirectional grinding is used, the formulae have to be modified to suit the requirements.

As stated earlier, only the general approach to estimation of cycle time is presented here. These have to be modified to suit the grinding technique and precess selected. Above all, process parameters, such as feed rates and infeeds, have to be valid because the quality of the cycle time estimate is vitally dependent on them. ■

References

1. Boothroyd, G. *Fundamentals of Metal Machining and Machine Tools*, McGraw-Hill, New York, 1975.

2. Dodd, H. and Kumar, D.V. "Technological Fundamentals of CBN Bevel Gear Finish Grinding," *Gear Technology*, Vol. 2, No. 6, November-December, 1985.

3. Dudley, D. W. *Gear Handbook*, 1st ed., McGraw-Hill, New York, 1962.

4. Schwartz, R. W. and Rao, S. B. "A Wheel Selection Technique for Form Gear Grinding." AGMA Paper No. 85FTM7, 1985.

5. Technology of Machine Tools, Vol. 3 Machine Tool Mechanics, UCRL-52960-3 LLL, Livermore, California, 1980.

6. Tlusty, J. and Koenigsberger, F. "Specifications and Tests of Metal-Cutting Machine Tools," *UMIST*, Manchester, England, 1970.

Acknowledgement: *From Dudley's Gear Handbook, 2nd. ed., Dennis P. Townsend, ed., ©1991 by McGraw-Hill. Reprinted by permission of McGraw-Hill Publishing Co.*