Parallel Axis Gear Grinding: Theory & Application

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Introduction

The goal of gear drive design is to transmit power and motion with constant angular velocity. Current trends in gear drive design require greater load carrying capacity and increased service life in smaller, quieter, more efficient gearboxes. Generally, these goals are met by specifying more accurate gears. This, combined with the availability of user-friendly CNC gear grinding equipment, has increased the use of ground gears.

Some of the first gear grinding machines were manufactured between 1910 and 1920, by both American and European machine builders. Improvements in machine design followed, so that by the late 1930s, extremely accurate gears were being ground. The equipment in use at that time, and for many years after, required operators having a very high level of skills.

While the same basic principles have been in use for gear grinding for many years, recent developments in CNC machines employing digital drives and sophisticated software have significantly changed the nature of the equipment used.

Advantages of Ground Gears

For many applications where gears transmit power at low speeds, or where loads are low and positional accuracy is not an issue, shaped, hobbed, or shaved gears will be adequate to meet the design requirements. As operating conditions become more demanding, gears of higher quality levels will be specified.

Hardened gears have increased strength and wear resistance, making it possible to reduce the size of the gears while increasing the load carrying capacity. This offers benefits in both economy and efficiency. Grinding is generally the preferred finishing method for hardened gears, particularly those which may have significant distortion due to heat treatment.

Gears manufactured from difficult-to-machine materials, such as high-temperature alloys, are frequently ground, abrasive machining often proving to be more economical than finishing by shaping or hobbing. In some cases, the gears or splines are ground from solid.

In addition to having accurate lead and involute profile, good quality ground gears have excellent tooth spacing: both pitch (tooth-to-tooth spacing), and index (cumulative spacing). Minimizing spacing errors provides better load sharing between teeth, resulting in greater bending fatigue resistance and lower noise.

Gear Grinding Methods

There are two basic methods of gear grinding—formed wheel grinding and generating grinding.

Formed Wheel Grinding. This method may be employed to finish either spur or helical gears (see Figure 1). If helical gears are to be ground, the machine will have a provision for setting the grinding wheel spindle to the helix angle of the gear and will be equipped to impart a slight rotary motion to the gear as it is ground. The grinding wheel is accurately dressed to the shape of the gear tooth space, the part is reciprocated axially past the wheel, and as the gear is ground, it is indexed to each tooth space. With appropriate equipment, formed wheel grinding machinery can be used to grind internal gears. Also, formed wheel grinding may allow the use of small diameter wheels to grind gears that are located near shoulders or other features that preclude the use of larger standard wheels.

Generating Grinding. In the generating method of gear grinding, the shape of the gear tooth is the result of the com-

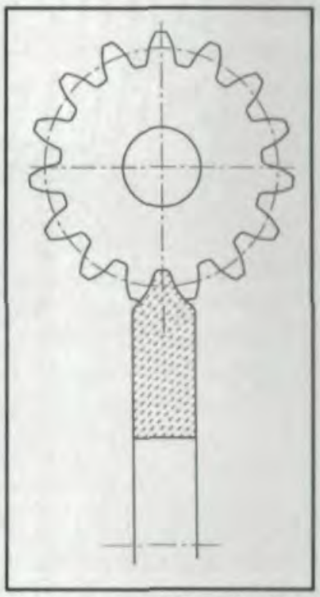

Fig. 1—Gear tooth form development by formed wheel grinding.

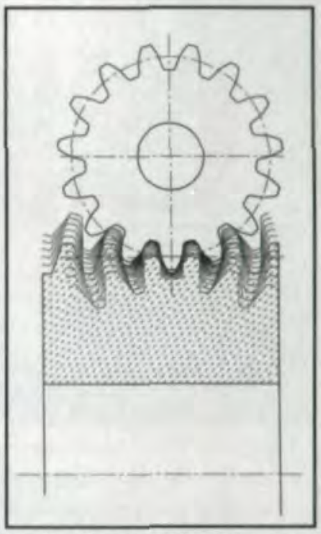

Fig. 2—Gear tooth form development by continuous generating.

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bined movements of the work piece and the grinding wheel, which is usually dressed to the shape of a rack tooth. Generating grinding is done by one of the following systems:

• Continuous generating gear grinding is done on a machine using a grinding wheel with a threaded rack tooth form similar to a worm (see Figure 2). The gear rotates continuously as it moves axially past the grinding wheel, which is fed in at the end of each stroke. The mechanics of the operation are analogous to hobbing.

• Single index generating involves grinding with a double-tapered wheel, which is dressed to the shape of a rack tooth (see Figure 3). The wheel is reciprocated as one tooth space is ground, while the work table feeds back and forth slowly at right angles to the gear's helix angle. After one tooth space is ground, the work indexes, the next space is ground, etc. Very large gears are usually ground using this method.

Gear Grinding Technology

Grinding Wheels. Regardless of the type of machinery used, selection of the appropriate grinding wheel is of utmost importance. Wheels are either aluminum oxide, ceramic (seeded gel), or cubic boron nitride (CBN). In addition to abrasive type, the grit size, wheel hardness and structure must be selected to produce an acceptable tooth form and surface finish without burning.

Traditionally, gear grinding has been done using aluminum oxide wheels; they are readily available in a variety of grades and sizes, and are easily dressed. In recent years, it has become more common

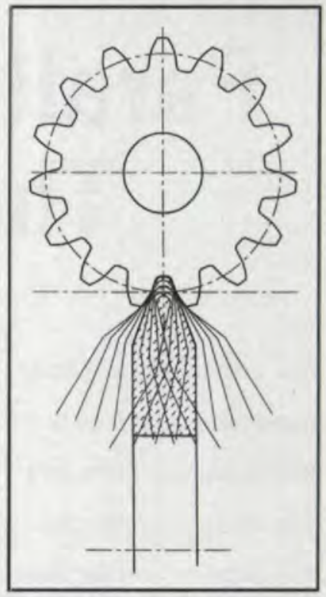

Fig. 3—Gear tooth form development by single-index generating.

to use ceramic wheels. Though they are somewhat more difficult to dress, their structure makes it possible to dress much less frequently. CBN wheels are either plated or dressable, with the plated wheels being much more commonly used. Disadvantages of CBN wheels are cost, particularly in situations where part volume is low, and the lead time required for wheel manufacturing.

Grinding wheel balancing is critical, particularly for larger size wheels. The wheels may be balanced on a dynamic balancing machine before mounting on the gear grinder. Alternatively, some grinders are equipped with automatic balancing equipment that maintains the balance of the wheel as it is in use.

Wheel Dressing. For many years, wheel dressing on any type of gear grinder was done using mechanical dressers equipped with single-point diamonds. Diamond tool setting was critical and diamond wear had to be very carefully monitored. Selecting the proper diamond traverse speed was crucial to produce the required surface finish. Successful wheel dressing was dependent upon the skill and experience of the machine operator. Currently available machinery is equipped with CNC dressing equipment, designed to use rotary diamond dressing rolls with either plated or hand-set diamonds. These combine the advantages of longer life with greater accuracy. Wheel dressing parameters have to be carefully developed to give both the gear tooth form and surface finish required. Software is available not only for involute gears and splines, but also for non-involute forms.

Tooling. One very important element in gear grinding is the workholding tooling used. No matter how accurate the grinding machine is, or how carefully the parts are processed, if the workholding or driving tooling is not properly designed, built and maintained, it will be impossible to consistently grind parts to the quality levels required.

Grinding Fluids. Coolants of various types are used to keep the grinding wheel clean and free-cutting and to prevent localized overheating or burning of the work, particularly on carburized and hardened gears. Carburized gears for critical applications are generally inspected after grinding by nital etching to reveal burning.

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Gear grinding is most often done using petroleum-based oils. As grinding wheel speeds have increased, particularly in applications where CBN wheels are employed, current trends are toward the use of less viscous oils. This reduces foaming and allows the use of refrigeration units to chill the oil, maintaining a constant temperature to reduce thermal expansion of both the work piece and the machine. In some cases, special oils have been developed specifically for gear grinding. For some applications, grinding may be done using water-based grinding fluids. Fluid maintenance has also become much more critical, generally using textile or paper filter media to remove abrasive and metallic fines from the fluid to help produce better surface finishes.

One of the things that requires operator attention is the correct placement of the grinding fluid supply lines. It is advantageous to have them placed as close as possible to the grinding wheel, positioned so that the rotation of the wheel will tend to carry the fluid into the grinding zone. As the wheel is dressed, it is necessary to occasionally reposition the nozzles.

A frequent source of environmental concern has been the airborne oil mist caused by oil being thrown from the

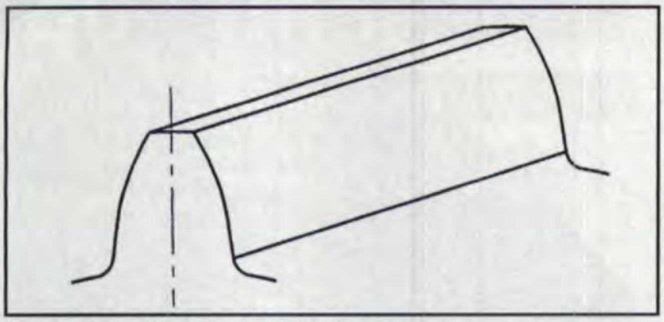

Fig. 4—Unmodified spur or helical tooth form.

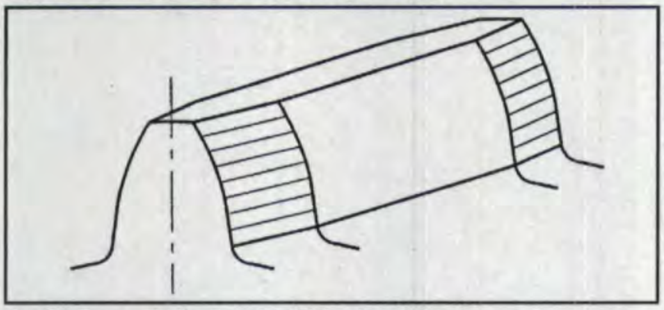

Fig. 5—Spur or helical tooth with lead modification.

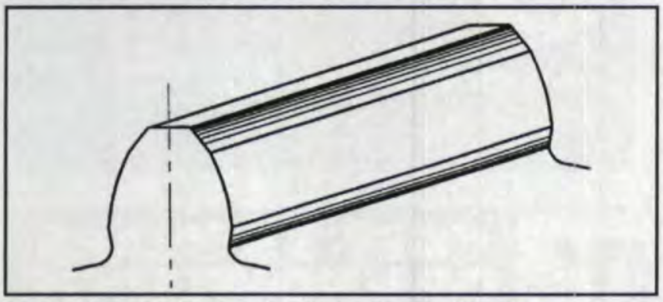

Fig. 6—Spur or helical tooth with involute modification.

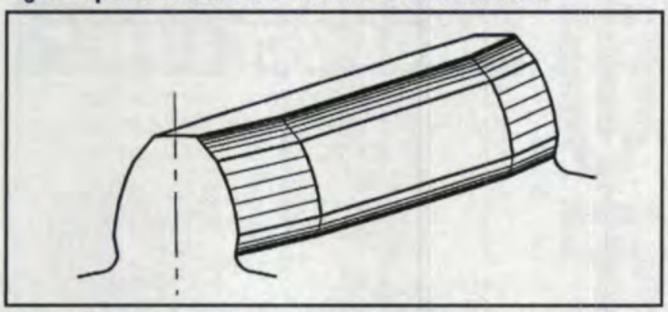

Fig. 7—Spur or helical tooth with both lead and involute modification.

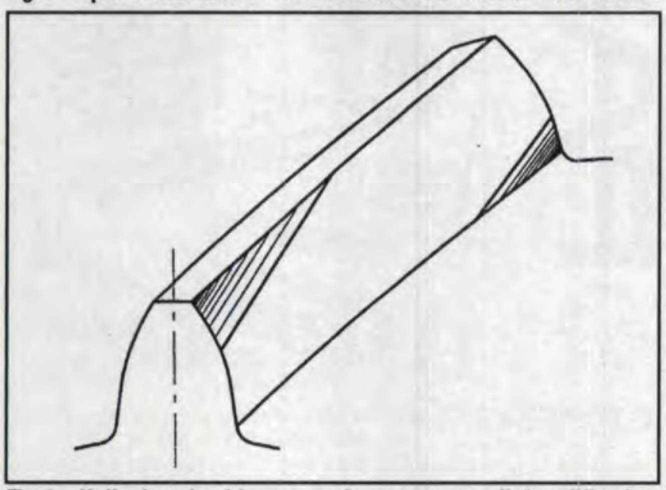

Fig. 8—Helical tooth with generated engagement relief modification.

grinding wheel at operating speeds. Machines now being built generally utilize an enclosure that helps contain the mist, combined with a recirculating air filtration unit.

Electronic Stock Dividing. One of the features of many recently-built gear grinders is automated equipment for locating the center of the tooth space before the grinding operation begins. This may be done by probing the tooth faces on one or more teeth, or by using a proximity detector. Accurate stock dividing allows equal stock to be removed from both flanks of the teeth. This is particularly useful in grinding carburized and hardened gears, where case depth is an important requirement. Some machine manufacturers have taken this a step further by identifying the widest space and dividing the stock at that point.

On-Machine Inspection. Another recent development is on-machine gear element inspection after grinding, sometimes including the capability of generating machine corrections automatically. Inspection is accomplished while the part is still mounted in the machine, using a probing system similar to a CMM with appropriate software. This is a particular advantage on larger workpieces, where work piece handling and fixturing are time consuming.

Gear Tooth Modification

Traditionally, gear tooth modifications on either spur or helical gears have been limited to involute modifications, removing a small amount of material at the tip and/or at the form diameter to compensate for tooth deflections under load, thereby providing more gradual tooth engagement (see Figure 6). This may sometimes be combined with a slight amount of lead modification (or crown), removing material at each end of the tooth face, to assure that the forces on the teeth are not concentrated at the ends of the teeth (see Figures 5 and 7). The negative effects of these strategies are that loads are distributed over smaller areas of the tooth surface, thereby increasing the contact stresses and the chance of surface fatigue failures.

Machines are currently available that allow topological grinding, thereby modifying the tooth flank profile on helical gears to allow gradual engagement and disengagement of each tooth pair, reducing noise and vibration and making possible smaller, more compact gearboxes. However, conventional profile and lead

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modifications are still the only choice for spur gearing, as tooth engagement occurs along the entire face width simultaneously.

The tooth engagement dynamics of helical gears are different. Initial contact occurs at the upper corner of each tooth, and the line of contact is diagonal to the tooth face. Therefore, it would be appropriate to introduce a modification that offers relief at the initial point of contact and runs parallel to the line of contact on the tooth (see Figure 8). At the American Gear Manufacturers Association 1996 Fall Technical Meeting, W. Kiess and S. Price of Höfler Maschinenbau presented a paper entitled, "Noise Reduction Through Generated Engagement Relief Modifications." Höfler is a German builder of gear grinding machinery. Recent advances in machines and controls have made possible the grinding of helical gears with this sort of tooth modification on single index generating-type machines. By allowing additional material to be removed from the tooth only at the points of engagement and disengagement, a larger tooth flank area is maintained and Hertzian contact stress is minimized. It is reported that helical gears modified in this manner have less measured vibration than unmodified gears, allowing designs that require less volume and weight. The results of research on the advantages of modified helical gears was presented by the late Dr. Eng. Kiyohiko Umezawa at the AGMA's 1998 Fall Technical Meeting in a paper entitled, "Low Vibration Design on a Helical Gear Pair" (see *Gear Technology*, Jan/Feb 2000). Topographic inspection equipment is available to monitor the engagement relief modification that is produced.

Conclusion

Gear grinding equipment has been available for over eighty years, providing a means of finishing high quality gears. Gear grinding may provide substantial savings in gear finishing costs. The machines that are currently available have features that reduce reliance on operator experience and skill while economically and consistently producing high quality gears in a way never before possible. ○

References

1. American Gear Manufacturers Association. "Gear Classification and Inspection Handbook," AGMA 2000-A88, 1988.
2. Kiess, W. and S. Price. "Noise Reduction Through Generated Engagement Relief Modifications," AGMA Fall Technical Meeting, 1996.
3. Townsend, D., Ed. "Dudley's Gear Design Handbook," McGraw-Hill, 1992.
4. Umezawa, Kiyohiko. "Low Vibration Design on a Helical Gear Pair," AGMA Fall Technical Meeting, 1998.

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