Gear Finishing by Shaving, Rolling & Honing - Part I

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There are several methods available for improving the quality of spur and helical gears following the standard roughing operations of hobbing or shaping. Rotary gear shaving and roll-finishing are done in the green or soft state prior to heat treating. These processes have the ability to modify the gear geometry to compensate for the distortions that occur during heat treatment. Gear honing is a particularly effective method of removing nicks and burrs from the active profiles of the teeth after heat treatment. Combined with its ability to improve surface finish and make minor form corrections, the honing process is rapidly being accepted as an operation through which many gears are processed following heat treatment.

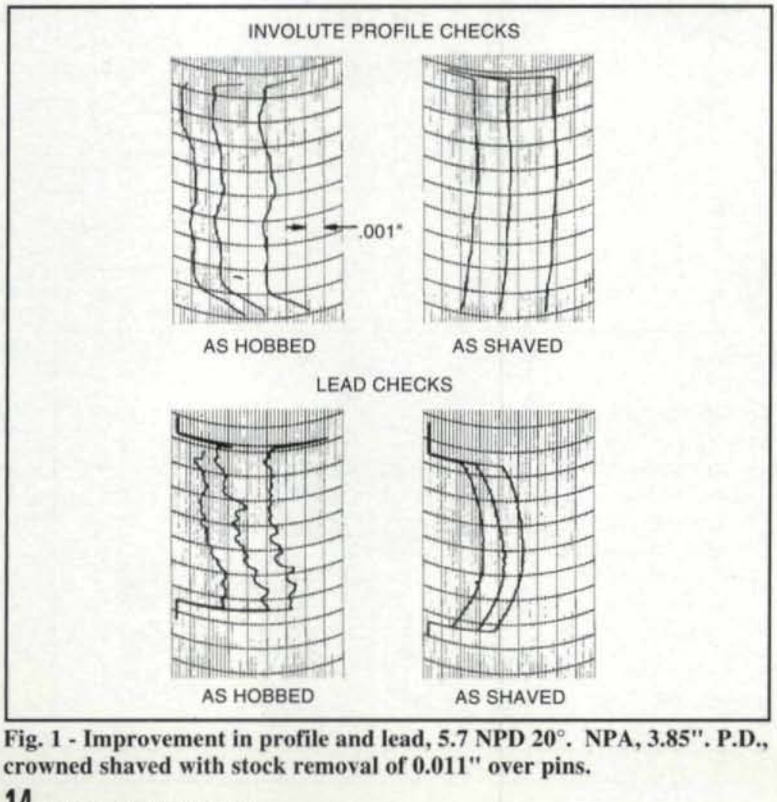

Fig. 1 - Improvement in profile and lead, 5.7 NPD 20°. NPA, 3.85". P.D., crowned shaved with stock removal of 0.011" over pins.

The Rotary Gear Shaving Process

Gear shaving is a free-cutting gear finishing operation that removes small amounts of metal from the working surfaces of gear teeth. Its purpose is to correct errors in index, helix angle, tooth profile, and eccentricity (Fig. 1). The process also improves tooth surface finish and eliminates, by crowned tooth forms, the danger of tooth end load concentrations in service. Shaving provides for profile modifications that reduce gear noise and increase a gear's load-carrying capacity, its factor of safety, and its service life. Gear finishing (shaving) is not to be confused with gear cutting (roughing). They are essentially different. Any machine designed primarily for one cannot be expected to do both with equal effectiveness or with equal economy.

Gear shaving is the logical remedy for the inaccuracies inherent in gear cutting. It is equally effective as a control for those troublesome distortions caused by heat treatment.

The form of the shaving cutter can be reground to make profile allowance for different heat-treatment movements due to varying heats of steel. The shaving machine can be reset to make allowance for lead change in heat treatment.

Rotary gear shaving is a production process that utilizes a high-speed steel, hardened and ground, ultraprecision shaving cutter. The cutter is made in the form of a helical gear. It has gashes in the flanks of the teeth that act as the cutting edges.

The cutter is meshed with the work gear in crossed axes relationship (Fig. 2) and rotated in both directions during the work cycle while the center distance is reduced incrementally. Simultaneously, the work is traversed back and forth across the width of the cutter. The traverse path can be either parallel or diagonal to the work gear axis, depending on the type of work gear, the production rate, and finish requirements. The gear shaving process can be performed at high production rates. It removes material in the form of fine hair-like chips.

Machines are available to shave external spur and helical gears up to 5m (200") in diameter. Other machines are also available for shaving internal spur or helical gears. For best results with shaving, the hardness of the gear teeth should not exceed 30 Rockwell C scale. If stock removal is kept to recommended limits and the gears are properly qualified, the shaving process will finish gear teeth in the 3.6- to 2.5-m (7-to 10-pitch) range to the following accuracies: involute profile, 0.005 mm (0.0002 in); tooth-to-tooth spacing, 0.0075 mm (0.0003 in); lead or parallelism, 0.005 mm (0.0002 in.)

In any event, it should be remembered that gear shaving can remove from 65% to 80% of the errors in the hobbed or shaped gear. It will make a good gear better. The quality of the shaved gear is dependent to a large degree on having good hobbed or shaped gear teeth.

Excellent surface finish is achieved with gear shaving. A value of approximately 25 μ in is the normal finish achieved with production gear shaving, although much finer finishes are possible by slowing the process. In some cases, shaving cutters will finish up to 80,000 gears before they need sharpening. They many generally be sharpened from four to ten times.

The shaving process offers attractive advantages in the ability to modify the tooth form. If a crowned tooth form or a tapered tooth form are desired to avoid end bearing conditions, these can be easily provided by shaving.

If modifications are desired in the involute profile, these can be made by suitable modifications in the ground cutter tooth form. If a crowned tooth form or a tapered tooth form are desired to avoid end bearing conditions, these can be easily provided by shaving.

Modifications in the involute profile can be made by suitable modifications in the ground cutter tooth form. If heat-treatment distortions can be controlled to a minimum, the most inexpensive way to produce an accurate, quiet, high-performance gear is to specify hobbing followed by gear shaving. The shaving process has a

Fig. 2 - Crossed axes meshing of shaving cutter and work gear.

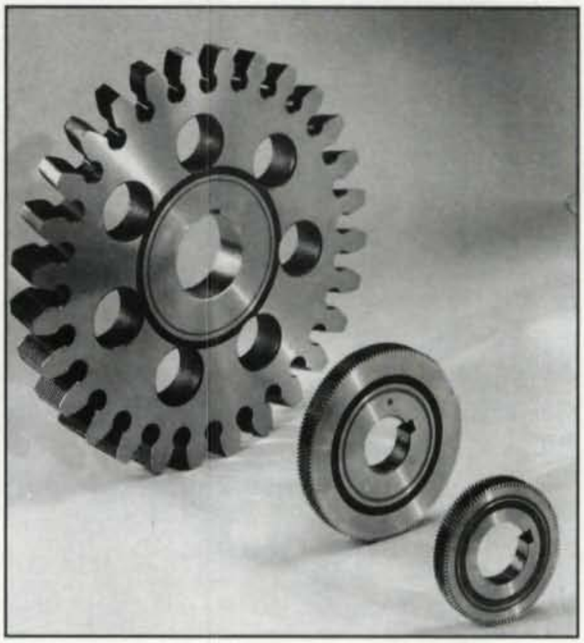

Fig. 3 - Assortment of rotary gear shaving cutters.

variety of standardized production equipment available, ranging from hand loading to fully automatic loading and unloading.

Basic Principles

The rotary gear shaving process is based on fundamental principles. This process uses a gashed rotary cutter in the form of a helical gear having a helix angle different from that of the gear to be shaved (Fig. 3). The axes of cutter and gear are crossed at a predetermined angle during the shaving operation. When cutter and work gear are rotated in close mesh, the edge of each cutter gash, as it moves over the surface of a work gear tooth, shaves a fine, hair-like chip. The finer the cut, the less pressure is required between tool and work, eliminating the tendency to cold work the surface metal of the

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Fig. 4 - 12" Rotary gear shaving machine.

work gear teeth.

This process is performed in a shaving machine (Fig. 4), which has a motor-driven cutter head and a reciprocating work table. The cutter head is adjustable to obtain the desired crossed axes relationship with the work. The work carried between live centers is driven by the cutter. During the shaving cycle, the work is reciprocated parallel to its axis across the face of the cutter and up-fed an increment into the cutter with each stroke of the table. This shaving cycle (conventional) is one of several methods.

The Crossed Axis Principle - To visualize the crossed axis principle, consider two parallel cylinders of the same length and diameter (Fig. 5). When brought together under pressure, their common contact surface is a rectangle having a length of a cylinder and width that varies with contact pressure and cylinder diameter.

When one of these cylinders is swung around so that the angle between its axis and that of the other cylinder is increased up to 90°, their common plane remains a parallelogram, but its area decreases as the axial angle increases. The same conditions prevail when, instead of the two plain cylinders, a shaving cutter and a work gear are meshed together. When the angle between their axes is from 10 to 15°, tooth surface contact is reduced and pressure required for cutting is small. As the work gear is moved away axially from the point of intersection backlash develops. Conversely, as it is returned to the point of axial intersection, backlash decreases until the two members engage in tight mesh with the teeth of the cutter wedging between those of the work gear. Thus, each succeeding cutting edge sinks deeper into the work gear tooth until the point of axial intersection is reached.

For shaving, the cutter and work gear axes are crossed at an angle usually in the range of 10 to 15° or approximately equal to the difference in their helix angles.

Crossing of the axes produces reasonably uniform diagonal sliding action from the tips of the teeth to the roots. This not only compensates for the nonuniform involute action typical of gears in mesh on parallel axes, but also provides the necessary shearing action for stock removal.

Relationship Between Cutting and Guiding Action - Increasing the angle between cutter and work axes increases cutting action, but, as this reduces the width of the contact zone, guiding action is sacrificed. Conversely, guiding action can be increased by reducing the angle of crossed axes, but at the expense of cutting action.

Preparation Prior to Shaving - The first consideration in manufacturing a gear is to select the locating surfaces and use them throughout the process sequence. Close relationship between the locating surface and the face of the gear itself must be held. Otherwise, when the teeth are cut and finished with tooling that necessarily contacts the gear faces, the teeth will be in an improper relationship with the locating or related surface on which the gear operates. Gears that locate on round diameters or spline teeth must fit the work arbors closely, or these critical hole-to-face relationships will be destroyed.

Typical manufacturing tolerances for gear blanks prior to cutting of the teeth are shown in Table 1.

Once the gear blank has been manufactured, it is necessary to cut the gear teeth. The most

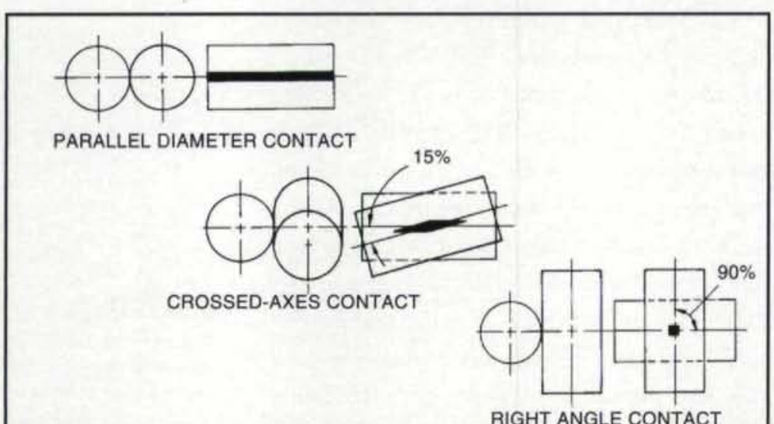

Fig. 5 - Contact between cylinders changes as crossed axes are varied.

Table I - Typical Gear Blank Tolerances

Blank Dia. In.	Face Runout In.	Hole Size In.	Hole Taper In./In.	Hole Roundness In.- Max	O.D. In.- Max	O.D. Runout In.
Up to 1, 1-in. Thick	0.0003- 0.0005	0.0003- 0.0006	0.0002- 0.0003	0.0002- 0.0003	0.003	0.003
1 to 4, up to 1-in Thick	0.0004- 0.0008	0.0005- 0.001	0.0002- 0.0003	0.0003- 0.0005	0.005	0.005
4 to 8	0.0006- 0.0012	0.0008- 0.0012	0.0002- 0.0003	0.0004- 0.0006	0.005	0.007
8 to 12	0.001- 0.002	0.001- 0.0015	0.0002- 0.0003	0.0005- 0.0007	0.005	0.008

common methods today for rough-cutting gear teeth are hobbing and shaper cutting. Of primary concern to the shaving cutter manufacturer is the fillet produced by the roughing operation. The tips of the shaving cutter teeth must not contact the gear root fillet during the shaving operation. If such contact does occur, excessive wear of the cutter results, and the accuracy of the involute profile is affected.

The shaving cutter just finishes the gear tooth below its active profile. Thus, the height of the fillet should not exceed the lowest point of contact between the shaving cutter teeth and the teeth on the work gear.

Protuberance-type hobs and shaper cutters are often used prior to shaving to produce a slight undercut or relief near the base of the gear tooth. This method assures a smooth blending of the shaved tooth profile and the unshaved tooth fillet, as well as reduces shaving cutter tooth tip wear (Fig. 6). The amount of undercut produced by the protuberance-type tool should be made for the thin end of the tooth. The position of the undercut should be such that its upper margin meets the involute profile at a point below its contact diameter.

Shaving Stock - The amount of stock removed during the shaving process is a key to its successful application. Sufficient stock should be removed to permit correction of errors in the preshaved teeth. However, if too much stock is removed, cutter life and part accuracy are effectively reduced.

Table 2 shows the recommended amounts of stock to be removed during shaving and the corresponding amount of undercut required.

Shaving Methods - There are four basic methods for rotary shaving of external spur and helical gears: (1) axial or conventional, (2) diagonal, (3) tangential or underpass, and (4) plunge. The principal difference among the various methods

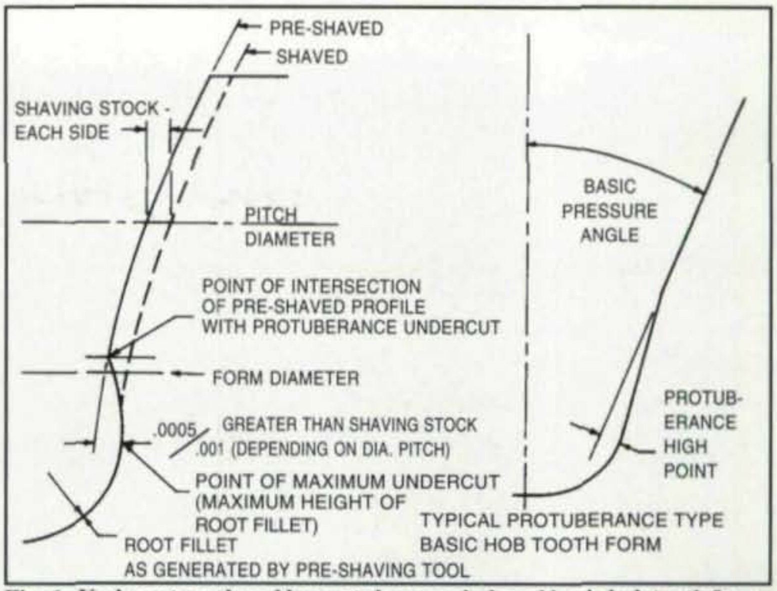

Fig. 6 - Undercut produced by protuberance hob and basic hob tooth form.

Table II - Recommended Shaving Stock and Undercut For Pre-shaved Gears

Normal Diametral Pitch	Shaving Stock (In. per Side of Tooth)	Total Undercut (In. per Side of Tooth)
2 to 4	0.0015 to 0.0020	0.0025 to 0.0030
5 to 6	0.0012 to 0.0018	0.0023 to 0.0028
7 to 10	0.0010 to 0.0015	0.0015 to 0.0020
11 to 14	0.0008 to 0.0013	0.0012 to 0.0017
16 to 18	0.0005 to 0.0010	—
20 to 48	0.0003 to 0.0008	—
52 to 72	0.0001 to 0.0003	—

is the direction of reciprocation (traverse) of the work through and under the tool.

Axial or Conventional - Axial shaving is widely used in low- and medium-production operations (Fig. 7). It is the most economical method for shaving wide-face-width gears. In this method, the traverse path is along the axis of the work gear. The number of strokes may vary due to the amount of stock to be removed. The length of traverse is determined by the face width of the work. For best results, the length of traverse should be approximately 1.6 mm (1/16") greater than the face width of the work, allowing minimum overtravel at each end of the

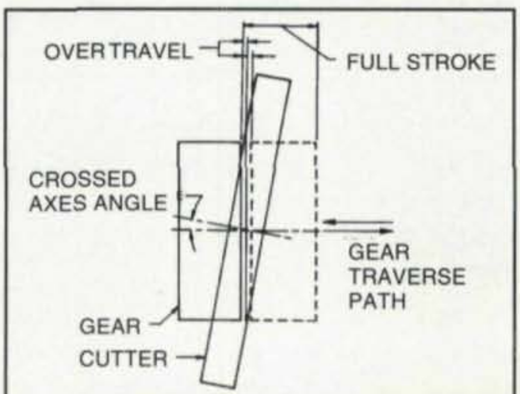

Fig. 7 - Axial shaving (conventional).

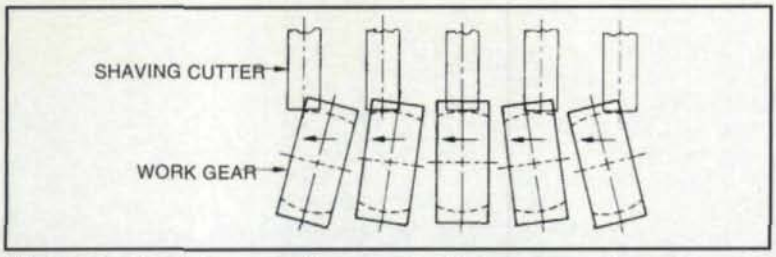

Fig. 8 - Rocking table action for crowning during conventional shaving.

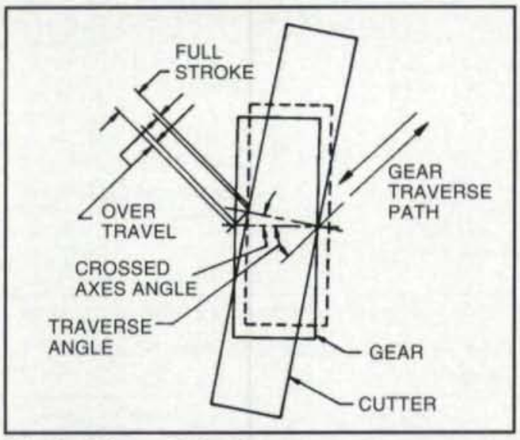

Fig. 9 - Diagonal shaving.

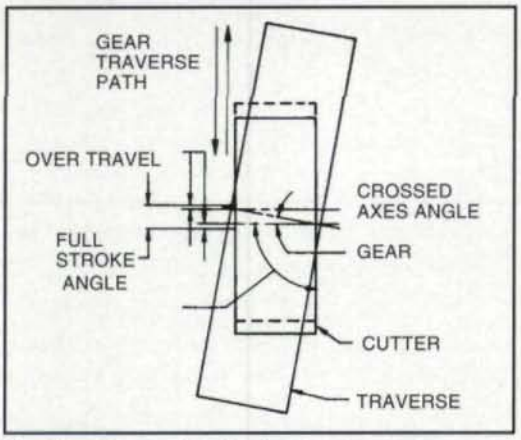

Fig. 10 - Tangential shaving (underpass).

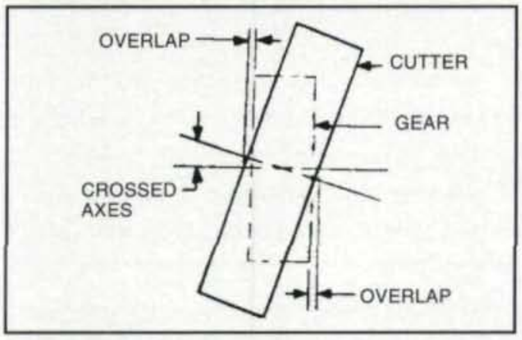

Fig. 11 - Plunge shaving.

work face. In axial shaving, in order to induce lead crown, it is necessary to rock the machine table by use of the built-in crowning mechanism (Fig. 8).

Diagonal - In diagonal shaving, the traverse path is at an angle to the gear axis (Fig. 9). Diagonal shaving is used primarily in medium- and high-production operations.

By use of this method, shaving times are reduced by as much as 50%. In diagonal shaving, the sum of the traverse angle and the crosses axes angle is limited to approximately 55°, unless differential-type serrations are used; otherwise, the serrations will track. The relative face widths of the gear and the shaving cutter have an important relationship with the diagonal traverse angle. A wide-face-width work gear and a narrow shaving cutter restrict the diagonal traverse to a small angle. Increasing the cutter face width permits an increase in the diagonal angle. Crowning the gear teeth can be accomplished by rocking the machine table, provided the sum of the traverse angle and crossed axes angle does not exceed 55°. When using high diagonal angles, it is preferable to grind a reverse crown (hollow) in the lead of the shaving tool.

In most cases, the diagonal traverse angle will vary from 30 to 60° to obtain optimum conditions of cutting speed and work gear quality.

With diagonal traverse shaving, the centerline of crossed axes is not restricted to a single position on the cutter as in conventional shaving, but is migrated across the cutter face, evening out the wear. Consequently, cutter life is extended. Although conventional shaving requires a number of table strokes, each with its increment of upfeed, diagonal shaving of finer-pitch gears may be done in just two strokes with no upfeed and a fixed center distance between cutter and work. An automatic upfeed mechanism on the shaving machine materially enlarges the scope of diagonal shaving by making it available for multistroke operations. This device feeds the work into the cutter in a series of small increments, synchronized with table reciprocation. Removing stock from the work gear in a series of small increments, instead of two large increments, further increases cutter life. It also makes the process feasible for gears requiring more stock removal than can be handled on a two-stroke cycle. When upfeed is completely automatic, there can be no danger of an error in selecting feed rates. Inasmuch as the cycle starts and stops in a position of maximum backlash, loading and unloading can be very fast.

Tangential or Underpass - In the tangential (underpass) method of shaving (Fig.10), the traverse path of the work is perpendicular to its axis. Tangential shaving is used primarily in high-production operations and is ideally suited for shaving gears with restricting shoulders. When using this method, the serrations on the cutter must be of the differential type. Also, the face width of the cutter must be larger than that of the work gear.

Plunge - Plunge shaving is used in high production operations (Fig. 11). In this method, the work gear is fed into the shaving cutter with no table reciprocation. The shaving cutter must have the differential-type serrations or cutting action will be impaired. To obtain a crowned lead on the work, it is necessary to grind into the shaving cutter lead a reverse crown or hollow. In all cases of plunge shaving, the face width of the shaving tool must be greater than that of the work gear. The primary advantage of plunge shaving is a very short cycle time.

Shaving Internal Gears - Internal gears can be shaved on special machines in which the work drives the cutter (Fig. 12), or by internal cutter head attachments on external shaving machines (Fig. 13).

Because of the crossed axes relationship between the cutter and the work gear in internal shaving, the cutter requires a slight amount of crown in the teeth to avoid interference with the work gear teeth. Crowning of the teeth on gears over 19 mm (3/4") wide is best achieved by a rocking action of the work head similar to the rocking table action with external gear shaving.

When internal gears are 19 mm (3/4") wide and under, or should interference limit the work reciprocation and crossed axes angle, plunge shaving can be applied. The cutter is provided with differential serrations and plunge-fed upward into the work. If lead crown is desired on the work gear, a reverse crowned cutter is used with the plunge feed shaving process.

The Shaving Cutter

Rotary shaving cutters are high-precision, hardened and ground, high-speed steel generating tools held to Class A and AA tolerances in all principle elements (Fig. 14). The gashes in the shaving cutter extend the full length of the tooth, terminating in a clearance space at the bottom. These clearance spaces provide unrestricted channels for a constant flow of coolant to promptly dispose of chips. They also permit uniform depth of serration penetration and increase cutter life.

The shaving cutter is rotated at high speeds up to 122m (400 and more surface ft.) per minute.

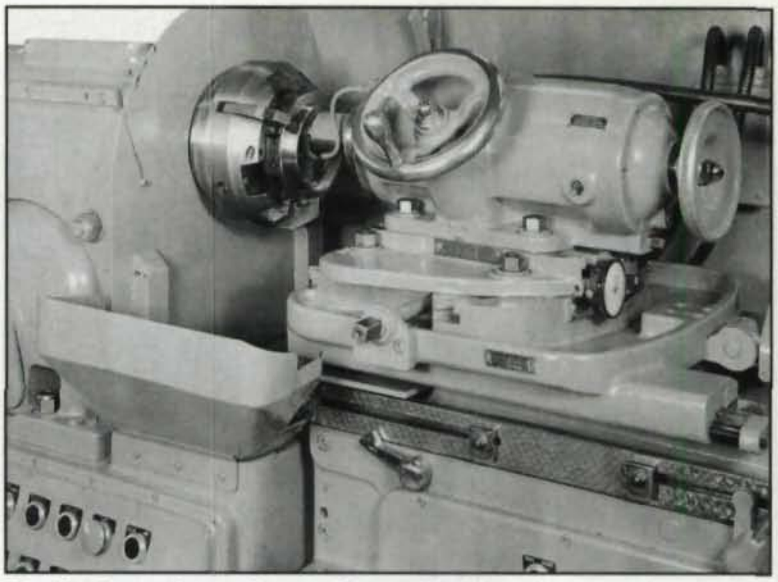

Fig. 12 - Internal gear shaver where tool is driven by the work.

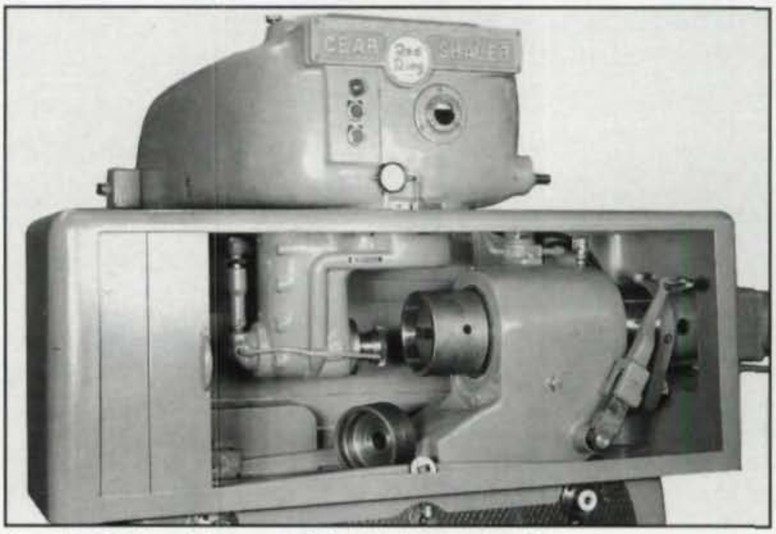

Fig. 13 - External shaver with internal cutter head attachment.

Feed is fine and the tool contact zone is restricted. Cutter life depends on several factors: operating speed, feed, material and hardness of the work gear, its required tolerances, type of coolant, and the size ratio of cutter to work gear.

Design - Rotary gear shaving cutters are designed much like other helical involute gears. The serrations on the tooth profiles, in conjunction with the crossing of the axes of the cutter and the work gear, make it a cutting tool. In designing rotary gear shaving cutters, the following are some of the points that must be considered:

1. Normal diametral pitch and normal pressure angle must be the same as those of the gears to be shaved.

2. Helix angle is chosen to give a desired crossed axis angle between the cutter and work. The crossed axis angle is the difference between the helix angles of the shaving cutter and work gear. The desired range is from 5 to 15°.

Fig. 14 - Variety of shaving cutters.

3. The number of teeth is chosen to give the appropriate pitch diameter required, considering helix angle and diametral pitch. Hunting tooth conditions and machine capacity are also important factors.

4. Tooth thickness of the cutter is selected to provide for optimum operating conditions throughout the life of the tool.

5. The addendum is always calculated so the shaving cutter will finish the gear profile slightly below the lowest point of contact with the mating gear. Tooth thickness and addendum of the cutter are not necessarily given to the theoretical pitch diameter.

6. Cutter serrations are lands and gashes in the involute profile of the tool. They extend from the top to the bottom of the tooth clearing into a relief hole at its base. The width or size is determined by the work gear to be shaved. Differential serrations with a control lead are produced on shaving cutters used for plunge shaving and diagonal with the traverse angle over 55°.

7. The involute profile of the shaving cutter tooth is not always a true involute. Very often, it must be modified to produce the desired involute form or modifications in the profile of the gears being shaved.

Sharpening Shaving Cutters - The shaving cutter, like other tools, dulls with use. In sharpening, minimum stock is removed on the tooth faces. With normal dullness, the resharpening operations usually reduce the tooth thickness approximately 0.74 mm (0.005"). An excessively dull or damaged tool must be ground until all traces of dullness or damage are removed.

The number of sharpenings varies with pitch and available depth of serrations. Usually a cutter can be sharpened until the depth of serrations has been reduced to approximately 0./15 to 0.30 mm (0.006 to 0.012").

Shaving Machines

Rotary gear shaving machines are manufactured in various configurations to meet the needs of the gear producing industry. Gears smaller than 25mm (1") and as large as 5.1 m (200") require different approaches. Rotary gear shaving utilizes a shaving machine that has a motor-driven cutter and a reciprocating work table. The cutter head is adjustable to obtain the desired crossed axis relationship with the work. The work carried between centers is driven by the cutter. Machines are available ranging from mechanical to one CNC axis to full five CNC axes.

During the shaving cycle, the work is reciprocated and fed incrementally into the cutter with each stroke of the table. The number of infeeds and strokes depends on the shaving method and amount of shaving stock to be removed.

The Machine Setup - Mounting the Work Gear. The work gear should be shaved from the same locating points or surfaces used in the preshave operation. It should also be checked from these same surfaces. Locating faces must be clean, parallel, and square with the gear bore. Gears with splined bores may be located from the major diameter, pitch diameter, or minor diameter. When shaving from centers, the true center angle should be qualified and the surfaces should be free of nicks, scale, and burrs. Locating points of work arbors and fixtures should be held within a tolerance of 0.005 mm (0.0002"). The arbor should fit the gear hole snugly. Head and tailstock centers should run within 0.005 mm (0.0002") for dependable results. Gears should be shaved from their own centers whenever possible. If this is not possible, rigid, hardened, and ground arbors having large safety centers should be used (Fig. 15). Integral tooling is another popular method of holding the work piece, especially in high production. This consists of hardened and ground plugs, instead of centers, mounted on the head and tailstock (Fig. 16). These plugs are easily detached and replaced when necessary. They locate in the bore and against the face of the gear. It is therefore essential that the gear faces be square and bore tolerances held to assure a good slip fit on the plugs.

Mounting the Cutter. Great care is required in handling the shaving cutter to avoid any accidental contacts between its teeth and other hard objects. The slightest bump may nick a tooth. Until the cutter is placed on its spindle it should lie flat and away from other objects. The cutter spindle and spacers should be thoroughly cleaned and the spindle checked before the cutter is mounted. The spindle should run within a 0.005 mm (0.0002") on the O.D. and 0.0025 mm (0.0001") on the flange full indicator reading.

After mounting, the cutter face should be indicated to check mounting accuracy. Face runout should not exceed 0.02 mm (0.0008") for a 30.5-cm (120") cutter; 0.015 mm (0.0006") for a 23-cm (9") cutter; or 0./01 mm (0.0004") for a 18-cm (7") cutter.

Feeds and Speeds. Shaving cutter spindle speeds will vary with the gear material hardness, finish, and size of part. Normally, when using a 18-cm (7") cutter on a 2.5-m (10-pitch) gear having a 7.6-cm (3") pitch diameter, spindle speed will be approximately 200 r/min; or, using a 23-cm (9") cutter, 160 r/min. This speed figured on the pitch circle is approximately 122 surface m (400 surface ft) per minute and this generally produces good results.

The following are formulae for determining cutter and gear speeds (r/min):

$$\text{Cutter r/min} = \frac{\text{desired surface speed per min}}{\text{cutter diameter} \times \pi}$$

$$\text{Gear r/min} = \frac{\text{cutter r/min} \times \text{number of teeth in cutter}}{\text{number of teeth in gear}}$$

For conventional shaving, about 0.25 mm (0.010") per revolution of the gear is considered a good starting point and becomes a factor in the following formula:

$$\text{Table feed rate [mm/min (in./min)]} = 0.25\ (0.010) \times \text{Gear r/min}$$

For diagonal shaving, an "effective feed rate" of approximately 1.0mm (0.040") per revolution of gear is considered a good starting point. Effective feed rate is the rate of the speed at which the point of crossed axes migrates across the face of the gear and shaving cutter. The following is the

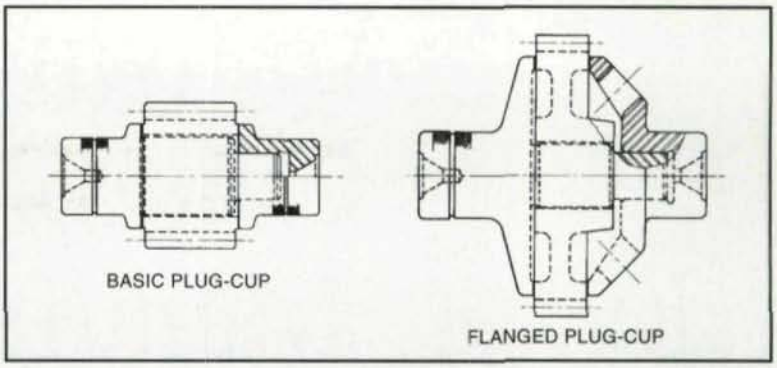

Fig. 15 - Typical hardened and ground work-holding arbors.

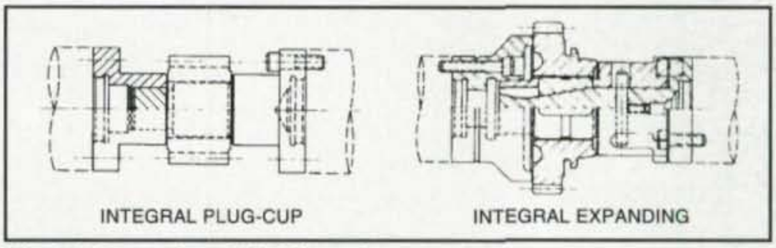

Fig. 16 - Integral work-holding arbors.

formula for determining the table traverse rate (in./min) to produce a 1.0-mm (0.040") effective feed rate:

$$\text{Table traverse rate [mm/min (in./min)]} = \frac{1.0 \text{ mm } (0.040") \times \text{Gear r/min}}{R_f}$$

where

$$R_f = \frac{\text{sine traverse angle}}{\text{tangent crossed axes angle}} + \text{cosine traverse angle}$$

These suggested feed rates may be varied depending on individual operating conditions. If higher production is desired, the table feed rate can be increased, but this may result in some sacrifice of the quality of tooth finish. Where surface finish is very important, as with aviation and marine gears, table feeds are reduced below the amounts indicated. In some cases (notably, large tractor applications), feeds considerably in excess of those indicated are used. ■

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This is the conclusion of Part I. Part II of this article, which will run in our next issue, will cover gear roll-finishing and rotary gear honing of both shaved and ground gears.