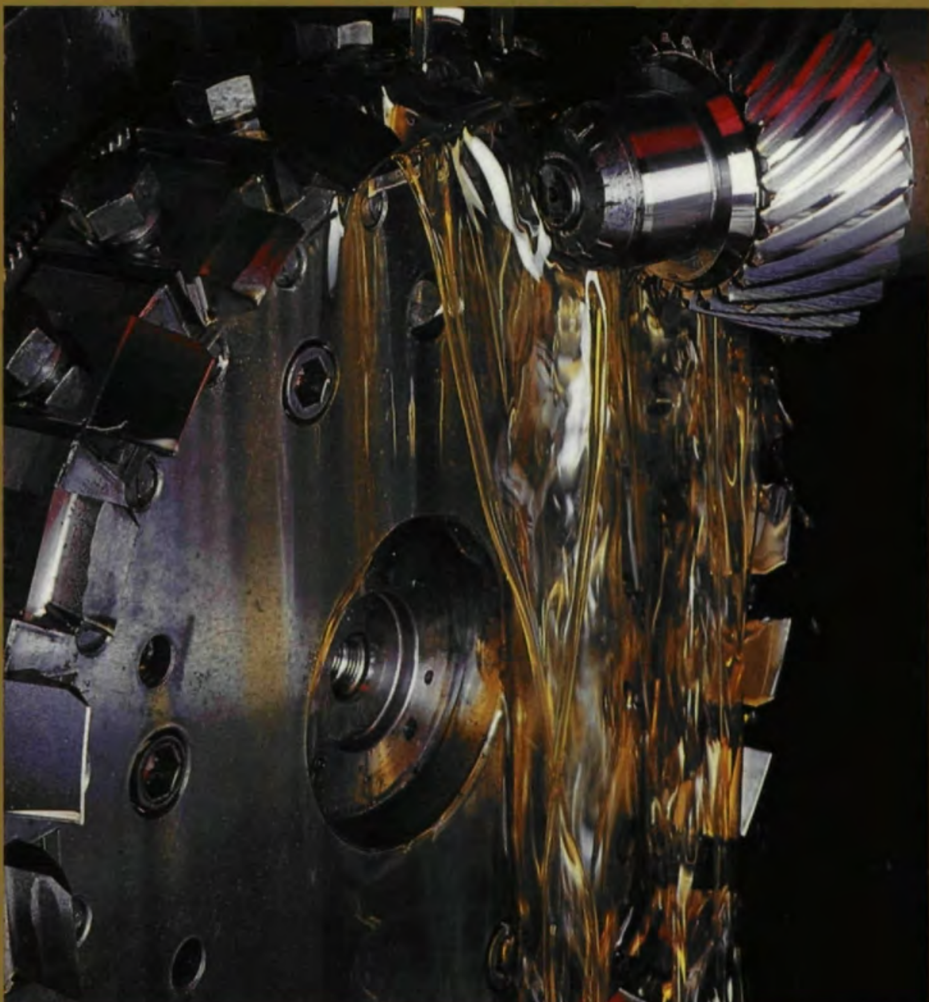
GEAR TECHNOLOGY

THE JOURNAL OF GEAR MANUFACTURING

MARCH/APRIL 1992



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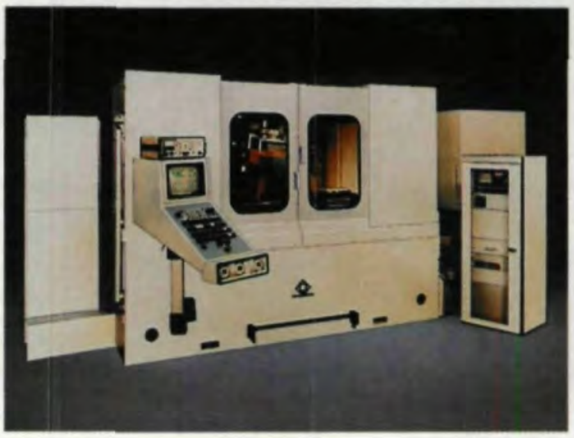

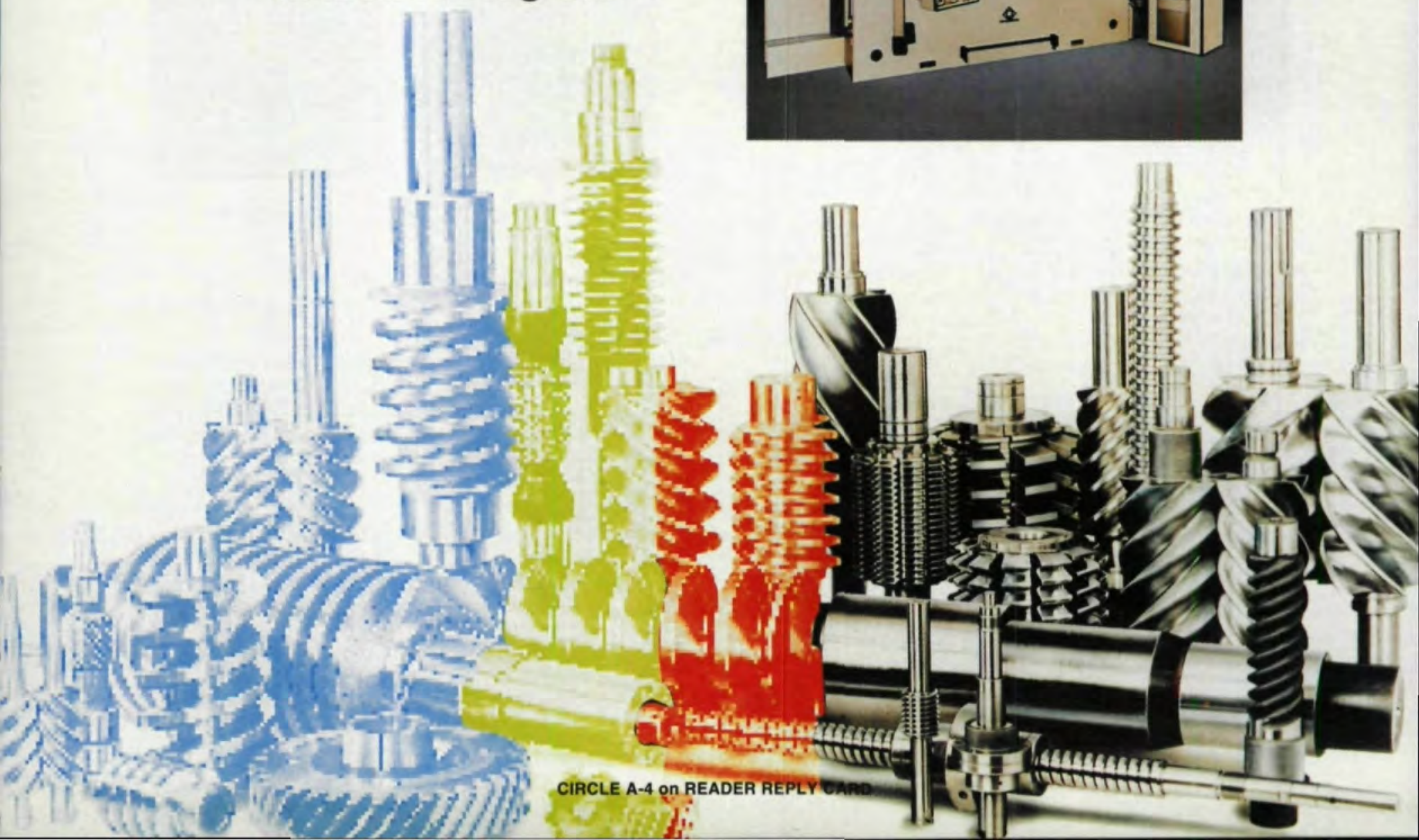

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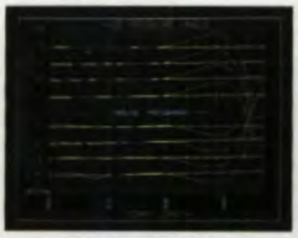

Hob Pressure Angle Check

Shaver Cutter Lead Check

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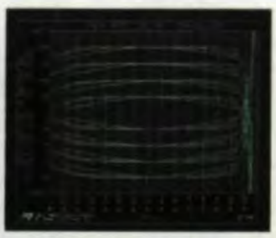

Modified K-Chart Analysis

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Investment Tax Credits - A Good Idea Whose Time Has Come

PUBLISHER'S PAGE

If timing is crucial in the successful implementation of good ideas, then now is the time to reinstate a good idea that fell into disfavor in the mid-1980s. Now is the time to include the investment tax credit as part of whatever inevitable tax structure tinkering is going to take place during this election year.

An investment tax credit, which gives companies an incentive to invest in capital equipment, has merit on a number of counts. One of the things our economy needs is a spur to large-scale investment that will give a payback beyond the short term. Investment in upgrading the tools of production is just such a spur.

A number of variations on the theme of the investment tax credit are being discussed around Washington these days. One is the president's proposal to grant a 15% tax credit to companies for the purchase of capital equipment. Basically, under that program, if you bought capital equipment worth $100,000 in a given year, you could take $15,000 off your total tax bill for that year.

Another proposal is to limit the credit to "productive equipment" like machine tools and computers. This would limit the total bill for the credit and would certainly benefit the gear industry.

As in the past, some have also suggested the possibility of including used machinery in the credit. This would have several advantages including creating a stronger market for trade-ins and encouraging companies to improve their technology. Such a credit would not appreciably hurt the sellers of new goods, since, most of the time, the buyer of used equipment is simply priced out of the market for new goods anyway.

A third proposal on the table is to make the investment tax credit something

like the one recently passed for research and development. Under this plan, the credit is incremental. It is paid out only on spending over and above an average spent on R&D between 1984-1988. Again, the incentive to upgrade and improve capital equipment is clear.

Each of the plans outlined has advantages and disadvantages. No doubt, before any changes in the tax laws come about, other new ideas will end up on the table as well. A number of our European friends either already have or are in the process of instituting just such plans. Italy is proposing to invest 1,500 billion lire over the next three years in its economy through such measures. The Italian government will give back to purchasers of capital equipment 10% of the equipment's cost in cash and allow them to write off 100% of the price on their taxes in the first year. In the UK, manufacturers are now campaigning for a 100% first year write-off for their investments in capital goods.

PUBLISHER'S PAGE

In my view, any ideas on investment tax credits deserve our full attention and that of our legislators. In an election year, when the temptation is to go for the quick and easy fix in exchange for votes, we have to make our feelings clear.

The need to make our economy more viable is of paramount importance. We as a country must invest in ourselves and in our industrial productive capacity, and changes in the tax code that will encourage spending on capital improvements will help us do that.

Congress must understand the importance of manufacturing to our nation's economic health. It's more than "important"; it's necessary that the tools we use in this country - whether they are machine tools, airplanes, tractors, or computers - are the best and most modern we can afford. It is the only way to maintain our competitiveness and the overall economic health of the nation.

If our leadership in Washington is serious about "jump starting" the economy, it should spend the money and take the action where it will do some good: on our industrial infrastructure. Give businesspeople the chance to upgrade their plants, buy the newer machinery they need to stay competitive and keep their employees on the payroll, and generate the kind of serious money that really will get the economy moving again. Those are the kinds of investments that will not only address the short term problem of the recession, but also are part of the response to the long term challenge to our economic health that America faces.

Michael Goldstein

Michael Goldstein
Publisher/Editor-in-Chief

A Hidden Treasure

Government Resources For Your Business

Rick Norment

At the next meeting of your association's marketing committee, notice what happens. The rate of taking notes increases dramatically when the market analysis and international trade trends reports begin. Even with the handouts to match the overhead projections of numbers, the audience's pace is furious. This is vital, apparently hard-to-come-by information, and no one wants to miss out. Almost all of the information comes from one source, yet the data offered is only one small dip from an enormous treasure chest - the U.S. government.

Washington is the best source of information about your major markets and their economic trends. Buried in the files of federal agencies is the data with which you can determine if your customers are in an expanding potential market, or one suffering from the onslaught of an import invasion. You can even gain a sense of the long range prospects for your customer markets, all from government information resources. There is also a wealth of programs to assist your company in market development, research and development, or manufacturing technology improvements.

Confidence in the federal government erodes with each new public opinion poll. While an understandable reaction to the less-than-favorable press reports about events in Washington, this is also unfortunate, since it tends to mask the fact that your government is a veritable treasure trove of valuable assistance.

One reason for this phenomenon is that government is not good at marketing. While the talent within various departments can be impressive, government program directors lack profit incentive or competition pressures and, as a result, are unfamiliar with how to promote participation in what really may be an excellent opportunity for business.

Another problem is the lack of a central clearinghouse. The government programs and information that can be of value to business are scattered throughout a variety of federal departments, agencies, and bureaus. For instance, programs to assist companies in their export efforts are found in 17 different government branches. The private sector has to ferret out these programs and resources, interpreting what it finds and putting it to work.

This process already has been highly developed by Fortune 500 companies, some associations, and many of our foreign competitors. Often Japanese businessmen outnumber their American counterparts visiting the Department of Commerce.

What are they looking for? Information, resources, and programs that can give businesses an "extra edge" in today's competitive market. It may be information about market trends - either U.S. or foreign. It may be information on how to be listed as a preferred supplier to a particular federal procurement agency. Or it may be public domain information about technologies developed at government expense or assistance in finding a qualified manufacturers representative overseas. It could be assistance in financing improvements to their plants. There are even travel funds available for potential foreign customers.

MANAGEMENT MATTERS

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Sorting Out The Options

As noted, by nature the government is not good at packaging and marketing what it has in the way of services or resources for business. For example, the U.S. government is a remarkable source of market information, both domestic and international. While everyone agrees the data is far from perfect, it is still generally

Rick Norment
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viewed as the best available anywhere. The trick is making sense out of how the data is maintained. With little understanding of the day-to-day operations of your business, the government keeps the information in a format that is convenient for its purposes, not yours. Businesses may have to interpret or even translate the information, but it still has enormous value in the process of making business planning decisions.

Remember that a significant part of all market statistics come from the federal government. Associations use this same data for summary presentations at many of their marketing council meetings. Expensive published reports have been generated solely from the same government data to which you have access, but you have the advantage of selecting the information most suited to you.

Maybe you are not a numbers person and prefer to get a "personal feel" for the market. Each of your customer markets has assigned to it an "industry specialist," usually in the Dept. of Commerce. That person can be a valuable observer for you, noting important trends and recent developments that can effect your company. A monthly phone call can help you keep your finger on the pulse of your markets.

Besides the Numbers, What Else?

The options are too many to list here, but here are a few examples:

•Following the example of the private sector, the government procurement agencies are moving to a smaller, more select list of suppliers. Contact these agencies and find out how to be designated as a qualified contractor. This designation can also have a ripple effect on current and potential customers, both in and out of government.

•The U.S. & Foreign Commercial Service of the Commerce Dept. will circulate your catalogue to potential foreign customers, help you find a foreign sales agent, and even assist in identifying customers for you.

•Under one Department of Commerce program, funding is available for groups of companies to open overseas offices (with the appropriate anti-trust exemptions for their operations).

•Other federal agencies can help you with the financing of export sales.

•Any federal agency with a research facility may be willing to sell you the results of its research and development programs. Remember, there are over 200 government labs which for years have been the principal sites for some very well-funded basic research. With Congress now eager to promote industrial competitiveness, these federal labs are eager to work with the private sector to provide cost-effective transfer of these new technologies.

•The shortage of skilled labor has finally come to the attention of the federal establishment. Many agencies, but particularly the Department of Labor, have programs to address the training needs of your employees. While it is more difficult for an individual company to get this support, local groups of companies (through their existing associations or ones created for this purpose) can obtain substantial funding for these activities.

Finding Your Way Around

The basic problem for American businesspeople is understanding where to start. For someone unfamiliar with the way federal agencies function, this can be a for-

midable task: the organization chart for a cabinet-level department can be intimidating. For example, a listing of the administrations, agencies, bureaus, and offices just within the Department of Commerce runs for 35 pages! Knowing some key words can often help break through the maze. Words like "liaison" and "small business," that appear in the name of the office in each department will serve as the tour guide or traffic cop for the outsider. At Commerce, it's the Office of Business Liaison; at the White House, it's the Office of Public Liaison.

The key phrase "small business" can mislead people, since it is defined by the federal government as any company with up to 500 employees (and for many industries, higher numbers than that). If you find a pairing of the terms, such as "small business liaison office," it can be of particular help. In each case, the people in these offices are not the problem solvers or program directors. Instead, their role is simply to direct you to the people that are.

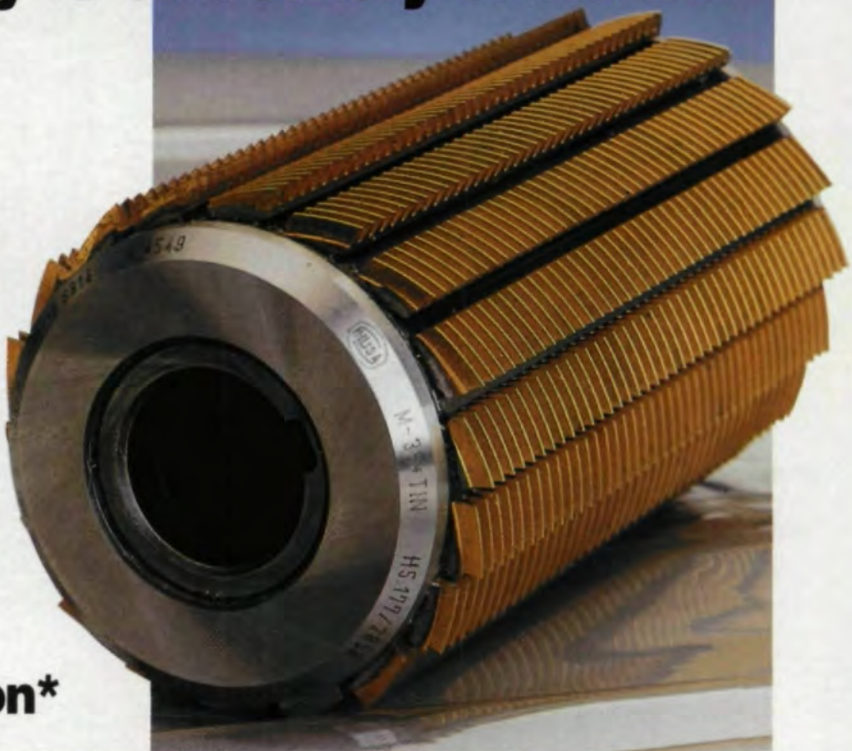
The Commerce Department is not the only agency with which you should be talking. Business programs are not all neatly housed in what might seem the single, logical agency. For example, if your principal markets relate to farming and the food industry, the Department of Agriculture is another contact you should make. Likewise, if you sell components that end up in weapons systems, talk to the Defense Department.

Once you have a name, title, and phone number, it can be as easy as a phone call. Most of these contacts are eager to help you. The problem is not getting a response from them; it is sorting through the options to discover what will work for you. Obviously, you know your business better than the government connection does, so with a mind open to new ideas, you may find a lot that will surprise you in the way of helpful resources.

The key to tapping the resources of the federal government is in the willingness of the private sector to go after these resources. Government is not structured to come knocking on your door to make an offer, but it is ready to help you. A couple of phone calls, or a visit to your local federal offices may offer you some surprising hidden treasures. ■

To address questions to Mr. Norment, circle Reader Service No. 80.

When Gear Quality is extremely critical...



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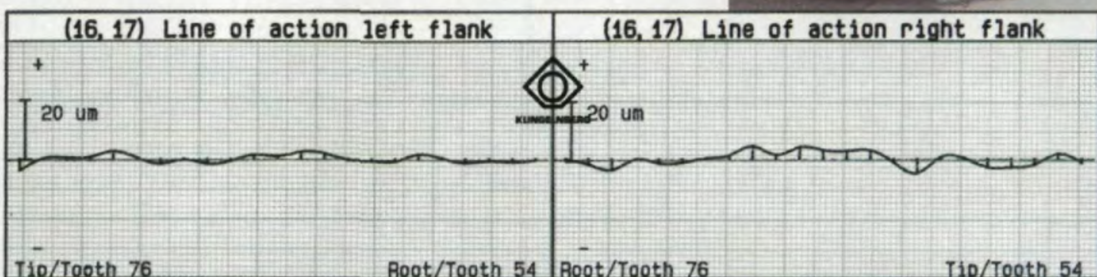

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Gear Finishing by Shaving, Rolling & Honing - Part I

John P. Dugas
National Broach & Machine Co.
Mt. Clemens, MI

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.

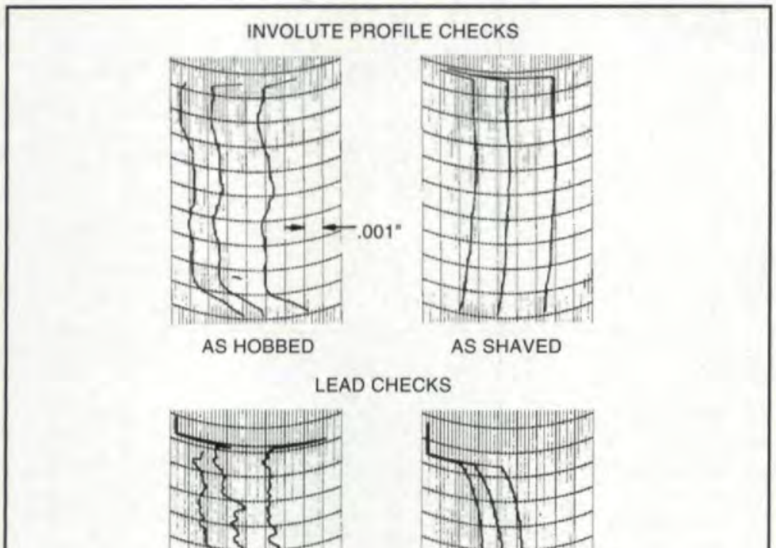

Fig. 1 - Improvement in profile and lead, 5.7 NPD 20°. NPA, 3.85". P.D., crowned shaved with stock removal of 0.011" over pins.

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

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

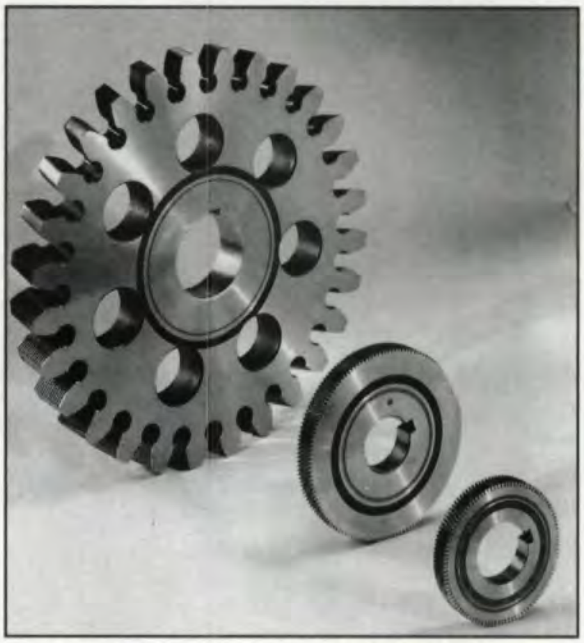

Fig. 3 - Assortment of rotary gear shaving cutters.

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.

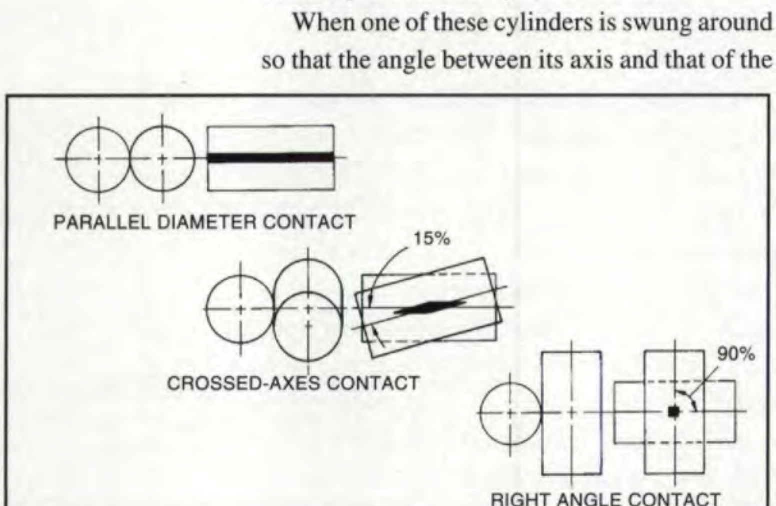

Fig. 5 - Contact between cylinders changes as crossed axes are varied.

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

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

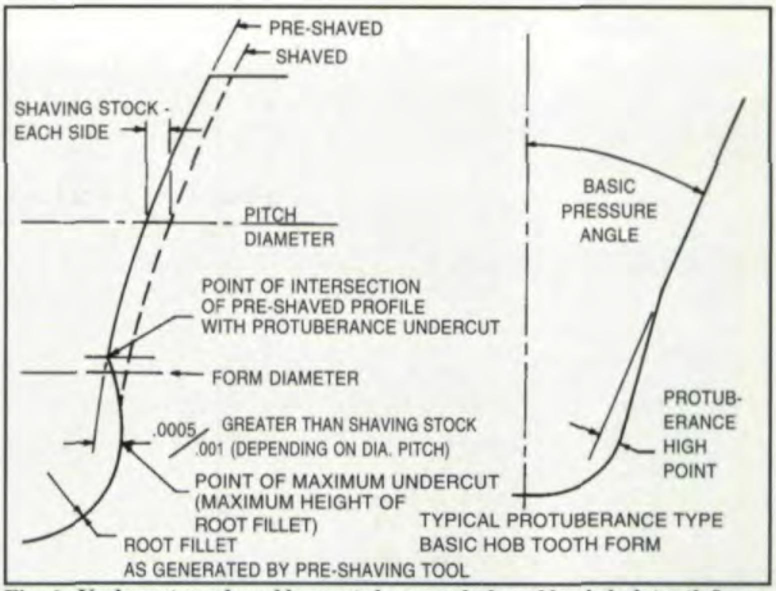

Fig. 6 - Undercut produced by protuberance hob and basic hob tooth form.

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

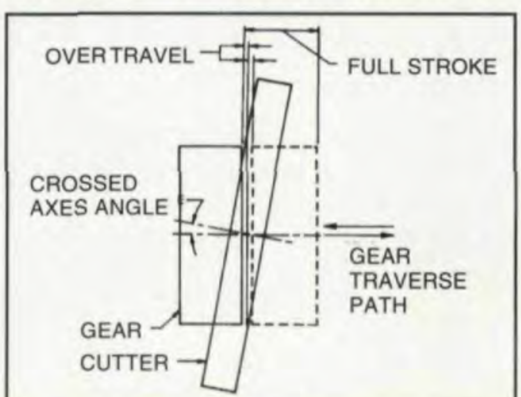

Fig. 7 - Axial shaving (conventional).

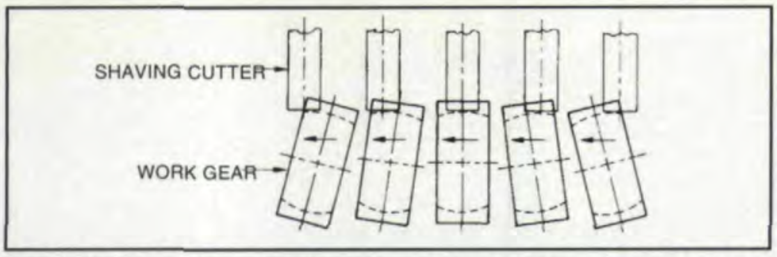

Fig. 8 - Rocking table action for crowning during conventional shaving.

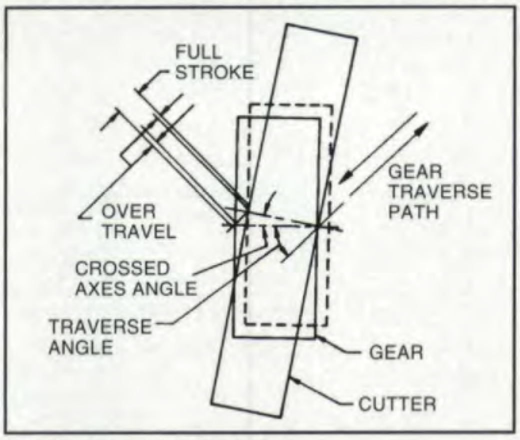

Fig. 9 - Diagonal shaving.

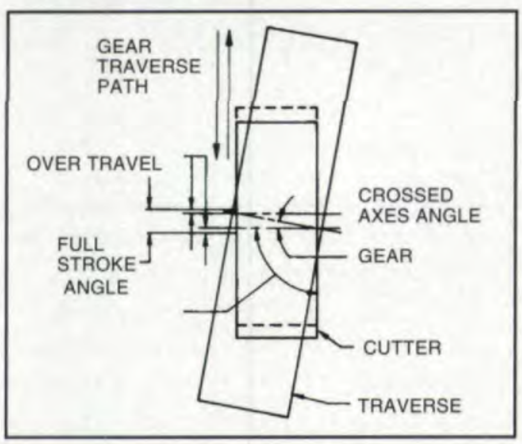

Fig. 10 - Tangential shaving (underpass).

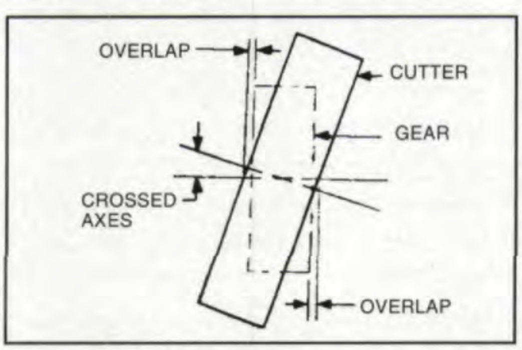

Fig. 11 - Plunge shaving.

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.

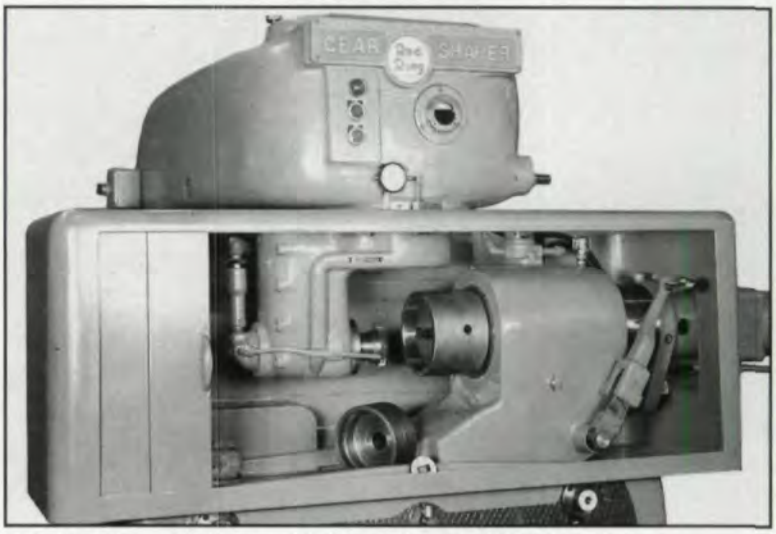

Fig. 13 - External shaver with internal cutter head attachment.

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°.

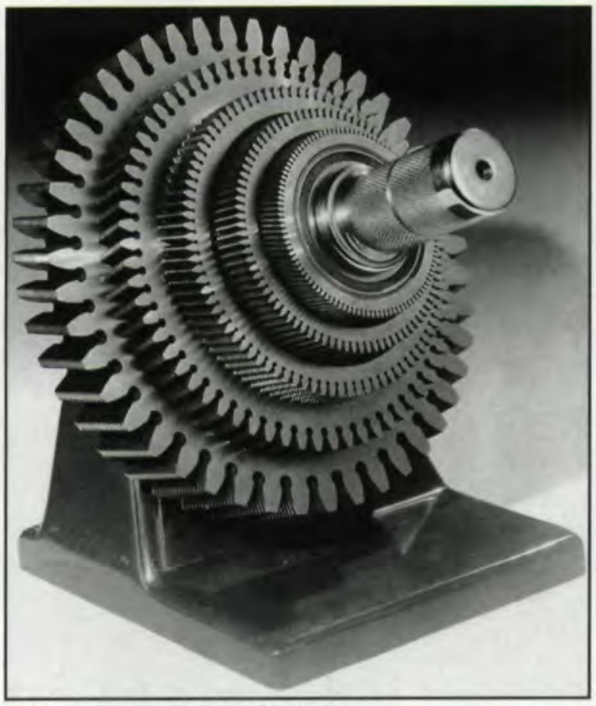

Fig. 14 - Variety of shaving cutters.

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

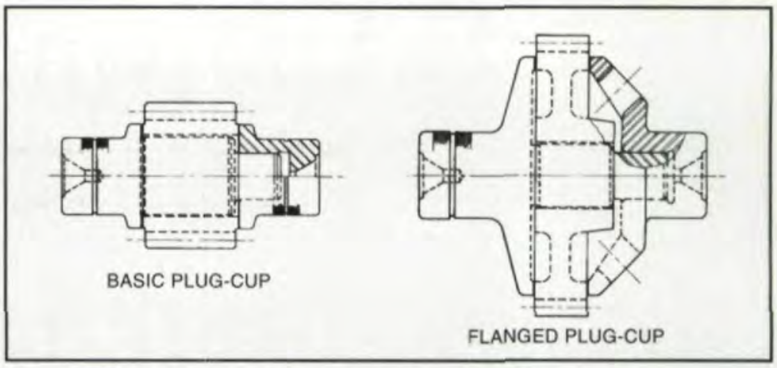

Fig. 15 - Typical hardened and ground work-holding arbors.

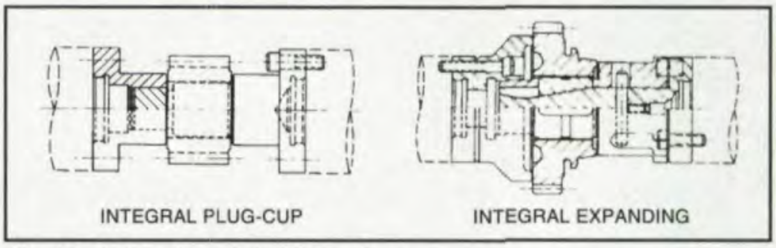

Fig. 16 - Integral work-holding arbors.

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.

Applying Process Control to Gear Manufacturing

Robert L. Sebetic
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Introduction:

A common goal of gear manufacturers is to produce gearing that is competitively priced, that meets all quality requirements with the minimum amount of cost in a timely manner, and that satisfies customers' expectations.

In order to optimize this goal, the gear manufacturer must thoroughly understand each manufacturing process specified, the performance capability of that process, and the effect of that particular process as it relates to the quality of the manufactured gear. If the wrong series of processes has been selected or a specific selected process is not capable of producing a quality part, manufacturing costs are greatly increased.

The manufacturing of a desired quality level of gearing is a function of many factors including, but certainly not limited to, the gear design, the manufacturing processes, the machine capability, the gear material, the machine operator, and the quality control methods employed. In this article we will make some basic assumptions about the gear design, engineering specifications, and the quality control methods employed, and concentrate mainly on the manufacturing processes, their control, and how they affect the gear quality produced.

Assumptions

In order to concentrate primarily on the gear manufacturing processes selected, their control, and how they affect gear quality, we have made several basic assumptions:

1. The gear designs are good, tooth contact analysis programs have been run, and motion curves and displacement values are within desired limits. Product testing and evaluation have been completed and found acceptable.

2. Engineering standards for accuracy and tooth contact location have been established according to design and testing requirements.

3. Acceptable quality control inspection methods are in place and GR&R studies (Gage Repeatability and Reproducibility) have been made, and the measured gage error has been deemed acceptable for all inspection measuring equipment and gages.

What Determines Gear Manufacturing Quality?

The quality level of a gear or gear set is determined during its manufacture by the specific sequence of production operations followed and the capability of each process. **The process sequence selected for the manufacture of a specific gear is determined by the final gear accuracies specified for that part.**

Two typical automotive/truck axle gear process flow diagrams are shown in this article. The target quality level of this type of gearing is generally set at AGMA 8. Example 1 (pg. 26) shows a general flow diagram of bevel gearing. Example 2 (pg. 27) is a general flow diagram of spur and helical gearing.

Note that it is possible, by the addition of a hard profile finishing operation after the heat treating operations, to increase the gear quality to AGMA 11 or 12. Along with this added operation, it may be necessary to tighten up some of the current manufacturing tolerances and to specify different workholding equipment. This would be primarily for bearing and bore diameters and could very easily affect the process capability of several different manufacturing operations.

What is Process Control?

Many gear manufacturers use process control techniques as a means of attaining the gear quality specified. AGMA defines process control as a method by which gear accuracy is achieved and maintained through control of manufacturing equipment, methods, and processes, without resorting to the inspection of individual elements of every gear produced.

Process control techniques analyze the manufacturing processes and quality control plans (METHODS), the gear steels used (MATERIAL), the machine capability (MACHINE), and the operator (MAN). When these techniques are properly applied to a specific process and that process is capable, then the gears manufactured will be of uniform quality.

How is the Process Monitored?

Data is collected on a specific characteristic for a specific process and then grouped in a histogram to get an idea of the distribution sample. With collected data, we can make some statistical calculations for the mean and the standard deviation. What we find is that the distributions will vary in shape, spread, and location relative to the tolerance, or any combination of the three.

The mean is defined as the sum of a group of numbers divided by the total number of elements within the group. The standard deviation is defined as the measure of dispersion (scatter or spread) of a set of data around its mean.

Statistical process control (SPC) techniques are excellent tools for evaluating a machine process. The results generated from an SPC evaluation give a "snapshot" picture of how the process is performing now and can be used to predict how it will perform in the future. These results can be used to compare the performance of other machines or processes and can be used to determine if a machine or process is capable of performing a specific task.

When is a Process "In Control"?

There are two causes of variation in any process. They are "common" and "assignable" causes. Common causes are random occurrences that are inherent to the process. They cannot be removed without changing the process. Generally, they are responsible for 85 to 90% of process variations. Assignable causes are non-random or patterned occurrences that can be identified and eliminated.

When conducting a capability study, material variations within one lot of material and variations caused by one operator may be significant; however, such variations are basic to the process and not easily eliminated. If there is no practical way of eliminating their influence on the process performance, these variations must be considered "common" variations.

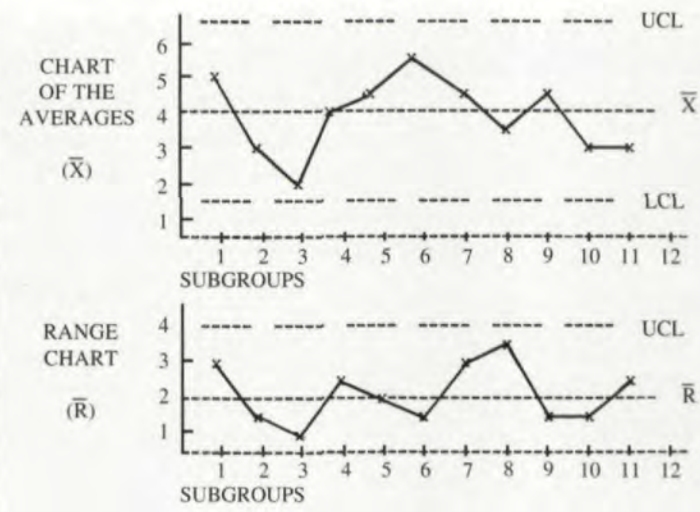

Fig. 1.

"Assignable" variations may come from many sources. A change in either operator from shift to shift or a material heat code lot change during the run are examples that can cause variation which is external to the basic process.

A process is said to be "in control" when the assignable causes have been eliminated. A process in statistical control will be evidenced on a control chart by the absence of points beyond the control limits and by the absence of non-random patterns or trends within the control limits (LCL, UCL). See Fig. 1.

What is Process Capability?

When the process is brought under control by eliminating the assignable causes, we can then assess its capability. It is important to note that a process "in control" may or may not be capable. Process capability is defined by two terms: Cp and Cpk.

Cp is the Process Capability Ratio. The Cp ratio is defined and calculated as follows:

Cp = Specification Tolerance Spread/(6 x Sigma), where Sigma is the standard deviation of the process being examined.

Basically, the Cp index is a comparison of the 6 Sigma spread of the distribution to the specification tolerance. Ideally, the 6 Sigma spread will fall within the specification toler-

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ance along with room to spare on each side of the specification limits. The Cp ratio does not account for centering the process relationship to the specification. See Fig. 2.

Cpk is the Capability Index. It gives an indication of the location of the distribution relative to the specification limits. Cpk accounts for the process centering.

For bilateral tolerances, when both upper and lower specification limits are given, Cpk is calculated by the following formula:

The minimum value of Cpk =
(USL - MEAN)/(3 X Sigma) or
(MEAN - LCL)/(3 X Sigma)

For unilateral tolerances, when only a minimum or maximum specification limit is given, Cpk is calculated by the following formula:

Cpk = (SL - MEAN)/3 Sigma

Where: USL = Upper Specification Limit
LSL = Lower Specification Limit
SL = Specification Limit
MEAN = Process Average
Sigma = Standard Deviation of Process

GIVEN PROCESS DATA:
MEAN = 17.5 SPECIFICATION TARGET = 16.5
STANDARD DEVIATION (SIGMA) = 1.3 TOLERANCE = +/- 5.5
Cp CALCULATIONS:
PROCESS SPREAD = 6 x SIGMA = 6 x 1.3 = 7.8
TOLERANCE SPECIFICATION SPREAD = UPPER SPEC. - LOWER SPEC. = 22.0 - 11.0 = 11.0

$$Cp = \frac{\text{TOLERANCE SPECIFICATION SPREAD}}{\text{PROCESS SPREAD}} = \frac{11.0}{7.8} = 1.41$$

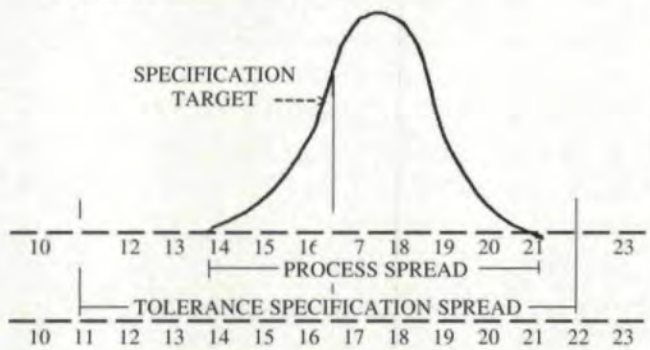

Fig. 2

Cpk calculation from data in Fig. 2:

$$Cpk = \frac{\text{UPPER SPECIFICATION LIMIT - MEAN}}{3 \times \text{SIGMA}}$$

$$= \frac{22.0 - 17.5}{3 \times 1.3} = 1.15$$

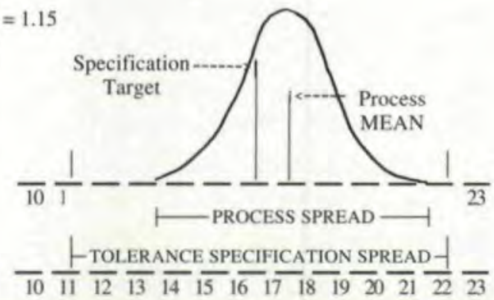

Fig. 3

Generally, the minimum accepted values for both Cp and Cpk are 1.33, which is equal to 75% of the tolerance for a 6 Sigma analysis. These indices give an indication of how well the process is making the product according to design or manufacturing specifications. Also, note that when the mean of the process is equal to the target value of the tolerance specification, then Cp = Cpk. The Cpk calculation from data in the previous example is shown in Fig.. 3.

It is also important to remember that the capability indices Cp and Cpk are based on two elements: the design tolerance and the standard deviation of the process. You can see, given the same data, we can change the tolerance to make the capability look better or worse for a given distribution. But the important element in the capability equation is the standard deviation (Sigma) of the measured distribution, and we cannot change that unless we change at least one of the process elements.

Applying Process Control - What Should Be Done?

In a word or two, **process control requires that the entire manufacturing process be examined from the forging coming in the door to the final shipment of the gear**. Where process capability studies are taken on each individual manufacturing operation to establish capability, control charts and plans must be maintained on a continuous basis to monitor performance capability. Also, do not forget the assumptions made in the beginning about the design, engineering specifications, and quality control methods employed.

Applying Process Control - Where Do We Start?

One of the most meaningful and eye-opening activities a gear manufacturer can pursue is the audit of several lots of finished gearing. Basically, it is a comprehensive self-assessment of your gear manufacturing capability. Select a variety of gearing based on pitch diameter, diametral pitch, and quality class required. Use lot sizes of at least twenty-five pieces and inspect all critical gear-related characteristics. Analyze the results using statistical methods. Now answer the following questions:

1. Are all the characteristics inspected within print specification?

2. After statistically analyzing the data, are the 6 Sigma values calculated less than the tolerance specification for that characteristic?

3. Are the data distributions centered with respect to the specification limits? Remember, Cp and Cpk values of 1.33 are generally the minimum accepted numerical value.

If the answers to Questions 1, 2, and 3 are "yes," and the calculated Cp and Cpk values are greater than 1.33, one should feel very confident about the quality of the overall gear manufacturing operation. Probably SPC techniques to monitor all manufacturing operations are already in use and the exact performance capability of each and every process in the plant is known.

If the answer to any one of the questions above is "no," there is work to be done. If the discrepancies are few and the manufacturing operation has a formal process control system in place, corrective action may not be much more than trouble-shooting a specific process operation. If the discrepancies are many, are critical characteristics, and the manufacturing operations are weak in the areas of SPC and process controls, a great deal of work will need to be done.

Applying Process Control - Perform Capability Studies

Knowledge of the performance capability of a process is essential to the overall concept of producing a quality gear. If the equipment selected and used is sufficiently accurate to meet quality requirements, an acceptable gear can be expected. When the quality is marginal or unsatisfactory, or when the processing equipment cannot meet the quality requirements, then the additional costs of scrap, rework, decreased productivity, and warranty result.

A process capability study is a technique for measuring that which a process is capable of producing under normal, in-control conditions. In a capability study, measurements of gears produced in a run are analyzed to determine whether or not the process is capable of producing, to specifications, a given characteristic on successive parts under production conditions. Process capability is a measurement of the inherent precision of a manufacturing process.

Applying Process Control - Identifying the Process Elements of a Capability Study

There are numerous combinations of manufacturing processes that can be used to produce an acceptable gear. Manufacturing engineering has the latitude to select the process to be used, depending on the capability of the equipment available and the available open capacity.

The results of capability studies show what is causing the "assignable" variation and what must be done to get it out of the process. Once this variation is eliminated, true process capability results.

In most processes, a capability study will show a large amount of initial variation. If capability studies have not been made on the process previously, the "assignable" variation is likely to be the greater part of the total variation. It is most likely the variation that gets the shop into the most trouble. The process capability study will work to detect and reduce or eliminate the "assignable" variation.

Table 1

1. MAN
   . Training on equipment and procedures
   . Work day fatigue/awareness
   . Setup skill & operating skill
   . Operator and operator changes
2. MACHINE
   . Quality capable
   . Machine alignment
   . Spindles
   . Draw
   . Speeds, feeds, and thermal growth
   . Rigidity
   . Balance
   . Machine maintenance & lubrication
3. MATERIAL
   . Material hardenability
   . Material chemistry
   . Microstructure
   . Hardness
   . Machinability
   . Material cleanliness
   . Dimensional characteristic
   (diameters, lengths, parallelism, runout)
   . Geometrical considerations
   (rims, webs, thickness, position)
4. METHODS
   . Workholding equipment type & condition
   . Workholding rigidity
   . Coolant type and volume
   . Cutting tool quality, new & resharpened
   . Cutting method
   (hob, shape, shear speed, mill, broach)
   . Material handling system

EXAMPLE 1
HYPOID/SPIRAL BEVEL GEAR AND PINION SET PROCESSING

GEAR

FORGING

PRE-TREATMENT NORMALIZE

BLANKING - PROFILE TURNING
- BROACHING
- *HOLE DRILLING*
- IDENTIFICATION

TOOTH CUTTING - MACHINE SETUP

GREEN TEST - CUTTING SETUP APPROVAL
- SIZE AND CONTACT COMPARISON TO PRODUCTION "REF".
- INSPECTION

BURRING, CHAMFERING

HEAT TREAT - CARBURIZE AND QUENCH
- BORE SIZE
- GEAR GEOMETRY

HARD GRIND - BORE I.D.

PINION

FORGING

PRE-TREATMENT NORMALIZE

BLANKING - PROFILE TURNING
- SPLINING
- GREEN GRINDING
- THREADING
- IDENTIFICATION

TOOTH CUTTING - MACHINE SETUP

GREEN TEST - CUTTING SETUP APPROVAL
- SIZE AND CONTACT COMPARISON TO PRODUCTION "REF"
- INSPECTION

BURRING, CHAMFERING

HEAT TREAT - CARBURIZE AND QUENCH
- INDUCTION ANNEAL
- STRAIGHTENING

HARD GRIND - BEARING JOURNALS

MATCH AND LAP OR HARD FINISH - REFINE TOOTH SURFACES FOR ACCEPTABLE TOOTH CONTACTS AND NOISE LEVEL

HARD TEST - MONITOR FINISHING OPERATION

PROTECT - PHOSPHATE COATING FOR BREAK IN, RUST PROOFING, AND IDENTIFICATION

SHIP - ASSEMBLY LINE OR CUSTOMER

To help identify "common" and "assignable" variations within a process, we would suggest that every process or operation that is analyzed be divided into four distinct categories, as shown in Table 1, and each category evaluated through the analysis of process elements. The four categories are 1) Man, 2) Machine, 3) Material, and 4) Methods.

Can We Sum This Up?

The gear quality level specified by the design dictates the processes used in your gear manufacturing to achieve that specified gear quality. Each process selected must be performance-capable over the long term to assure that the quality is maintained from one operation to the next. Audits of finished product must be conducted on a regular basis.

If quality defects occur, use process capability techniques to identify and fully understand the root causes of the problems and the paybacks associated with fixing them. After identifying the problems, use the Pareto principle to determine the areas of the highest payback. Develop a gear quality group, a game plan, and start small. After several successes are achieved, the quality group can grow aggressively and take on more quality problems.

Once process control techniques are employed, a gear manufacturer generally realizes tremendous benefits. One of the spin-offs of this type of analysis is that it will not take long before most gear manufacturers will want to make some fundamental changes in the manufacturing process to improve quality, improve productivity, or to implement some cost reduction projects. This comes from the thorough understanding of the process and its present capability.

There are many days we all struggle with gear quality issues. They consume a great deal of our time and effort. There can be a great deal of frustration; but in today's competitive environment, a formal process control system in place is essential no matter what product is manufactured. ■

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EXAMPLE 2
SPUR/HELICAL GEAR AND PINION PROCESSING

GEAR OR PINION

FORGING

PRE-TREATMENT NORMALIZE

BLANKING
- PROFILE TURNING
- HOLE DRILLING, BROACHING, SPLINING
- KEYWAY, THREADING
- IDENTIFICATION
- "GREEN" GRINDING

TOOTH CUTTING
- HOBBING, SHAPER CUTTING, SHEAR SPEED, MILLING, ROLLING
- SHAVING

GEAR INSPECTION
- CUTTING SETUP APPROVAL
- PIN DIMENSION
- LEAD, CROWN, AND INVOLUTE FORM
- PRECISION INDEX

CHAMFERING, BURRING, ETC.

HEAT TREATMENT
- CARBURIZE & QUENCH, NITRIDE, INDUCTION HARDENING, ETC.
- INDUCTION ANNEAL
- BORE SIZE, SPLINE SIZE, ETC.
- TOOTH SIZE AND TAPER
- RUNOUT, STRAIGHTENING, ETC.

HARD GRINDING
- BORE AND FACE LOCATIONS
- BEARING DIAMETER, JOURNALS, ETC.

SPEED OR HONE
- MONITOR MANUFACTURE
- NICK AND KNOT REMOVAL

HARD PROFILE FINISHING

CUSTOMER
- ASSEMBLY
- OUTSIDE CUSTOMER

Gear Hardness Technology

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Introduction:

In a very general sense, increasing the hardness of a steel gear increases the strength of the gear. However, for each process there is a limit to its effectiveness. This article contains background information on each of the processes covered. In each section what is desired and what is achievable is discussed. Typical processes are presented along with comments on variables which affect the result. By reviewing the capabilities and processes, it is possible to determine the limits to each process.

Throughout this article several hardness scales are mentioned. The abbreviations for these scales are as follows:

BHN - Brinell hardness number
KHN - Knoop hardness number
HRC - Rockwell "C" scale
HV - Vickers hardness number

Preliminary Heat Treatment Processes

There are several heat treatments performed during the manufacturing process which are intended to condition the metal for manufacturing. Since these are essential processes they will be described briefly.

Annealing. Annealing is a process in which a part is heated and then slowly cooled in the furnace to 600°F (316°C). Full annealing involves heating to a temperature above the upper critical (A_3 point). This will result in softening the part and improving the machinability. Intercritical annealing involves heating the part to a temperature above the A_1 point, but below the A_3 point. Finally there is subcritical annealing, which heats the part to just below the first transformation temperature (A_1), as in tempering, and slow-cools it, just as in full annealing. Subcritical annealing is often done to stabilize the structure prior to carburizing.

Normalizing. Normalizing is a process which involves heating the part to above the upper critical as in annealing, but it is cooled outside the furnace in still or agitated air. Normalizing is done to relieve residual stresses in a gear blank and for dimensional stability. A normalized part is very machinable, but will be harder than if it were annealed.

Stress Relieving. Stress relieving is heating to below the lower transformation temperature, as in tempering, and cooling in air. This is done primarily to relieve internal stresses. This process is sometimes called process annealing.

Through Hardening

Through hardening refers to heat treatment methods which do not produce a case. This term does not imply that the hardness is uniform throughout the gear tooth. Since the outside of a gear is cooled faster than the inside, there will be a gradient in the hardness. The achievable hardness is based on the amount of carbon in the steel. The depth of hardness depends on the hardenability of the steel.

For the purposes of this article, we will concentrate on the quench and temper process. This method is used to obtain the final core properties of the material for gears which are either cased or not cased. When this process is used to develop the core properties for nitrided gears, it is done prior to the nitriding cycle. When it is used to harden a carburized gear, it is done after the gear has been carburized. For gears which are not cased, the load carrying capacity of a gear is dependent on the core hardness of the material. (The capacity of case-hardened gears is primarily dependent on case hardness). It is generally accepted to use the hardness value measured at the root diameter in the center of the tooth when making comparisons.

Depending on the loading the gear must handle,

Table 1 - Common Through Hardened Gear Steels

Steel	C	Mn	S max	P max	Si	Cr	Mo	Ni
AISI 1045	0.45	0.75	0.050	0.040	—	—	—	—
AISI 4130	0.30	0.50	0.040	0.035	0.30	0.95	0.20	—
AISI 4140	0.40	0.90	0.040	0.035	0.30	0.95	0.20	—
AISI 4145	0.45	0.90	0.040	0.035	0.30	0.95	0.20	—
AISI 4340	0.40	0.70	0.040	0.035	0.30	0.80	0.25	1.83
AISI 8640	0.40	0.90	0.040	0.035	0.30	0.50	0.20	0.55

Table 2 - Approximate Quenching Behavior of 4140 and 4340 Steel				
Quench Effectiveness	Quench time to 500°F, seconds		Structure to be expected	Notes:
	4140	4340		
A	25	80	Excellent (over 90% martensite)	1. A structure not quenched out to full martensite will not be fixed up by tempering.
B	80	200	Reasonably good (martensite and some other transformation products)	2. Material in the "F" situation could be tempered to meet about 300 Brinell minimum. (The "as quenched" hardness would be above 300 HB.)
C	200	600	Less good, but may be acceptable (martensite, bainite, pearlite, and perhaps some free ferrite)	3. Material in the "F" situation would probably fail to meet Charpy V notch and ductility requirements normally expected for a good steel. In addition, the fatigue strength would be poor.
D	300	1000	Poor, usually not acceptable for high performance parts (low in martensite, with much bainite, pearlite, and free ferrite)	4. Poor quenching results can result from things like an improper prior structure or the wrong austenitizing temperature. (A slow quench is not the only reason for a poor structure.)
F	800	7000	Very poor, usually not acceptable (pearlite, free ferrite, some bainite, maybe some martensite)	

it is often necessary to increase the hardness of the steel. According to AGMA standards,[1] a gear with a hardness of 400 BHN, which has a design life of 10^7 cycles, can handle as much as 20% more load than a gear which is hardened to 300 BHN. For hardnesses above 400 BHN the capacity increases with respect to pitting resistance, but the capacity decreases with respect to bending strength, which deteriorates because the tooth becomes brittle.

Though a great deal of attention is given to the hardness of the material, it is important to understand that the microstructure, upon which the hardness depends, is what really matters. Although in-depth discussion of microstructure is beyond the scope of this article, it is worth mentioning that the degree of martensitic structure is one of the prime indicators of a material's quality. AGMA 2004-B89[2] does a good job of identifying other microstructural aspects that must be considered.

Unlike most gear heat treatments, through hardening is a process which can be performed either prior to or after the gear teeth are cut. The hardness is achieved by heating the material to the austenitic range (usually to about 1500-1600°F) and than quenching and tempering. For situations when the teeth are cut after the material has been hardened, machinability becomes a consideration in determining the hardness. For the most part, conventional gear cutting processes (hobbing, shaping, or milling) are capable of cutting materials with hardnesses of up to 400 BHN. Though 400 BHN is machinable, gear teeth are much easier to machine when the hardness is lower. There will be distortion if the hardening is done after the teeth are cut. The teeth may have to be finish-machined to achieve the required accuracy.

The Process. To harden a part by this process, the part is heated to the austenitic range, a temperature that varies, depending on the carbon and alloy content, within the range of about 1500-1600°F (815-870°C). In this state the steel becomes austenite, which is a term for the solid solution of carbon in fcc iron.[3] Then the part is rapidly quenched in oil (or sometimes water) to transform the austenite into martensite. If the quench is too slow, the structure will not be fully transformed to martensite. The resulting microstructure will then contain what are called transformation products, such as ferrite, bainite, pearlite, and cementite. The properties of hardness, toughness, ductility, and strength are dependent on the transformation products which are present.

The rate of cooling which must be achieved to properly transform the steel to martensite and minimize the percentage of transformation products is dependent on the chemistry of the alloy being used. The amount and type of alloying elements in the steel determine its hardenability.

Hardenability is a measure of the relative depth to which hardness is achieved for a given quench rate and section thickness. In other words, a material with a high hardenability, which is quenched at the same rate as a part of the same size, but with low hardenability, will have hard material deeper.

The alloying elements which have an impact on the hardenability of the steel are manganese, chromium, nickel, and molybdenum. Table 1 is a table showing several alloy steels which are commonly used for through hardened gears. A material such as AISI 4140 is considered to be a low alloy steel and has rather poor hardenability. A material such as AISI 4340 is considered to be rich alloy steel and has much better hardenability.

Once the part has been quenched, it needs to be

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Table 3 - Approximate Carbon Content to Develop Maximum Hardness in Carburized Case of Nickel Alloy Steels			
		Carburized Case	
Steel Type	Quenching Cycle	Carbon Content for Max. Hardness, %	Maximum Rockwell C Hardness
2315	DQ	0.80	63
2515	DQ	0.80	62
3120	DQ	0.90	65
4320	DQ	0.90	67
4320	RH	0.85	66.5
Krupp[b]	DQ	0.60	61
Krupp[b]	RH	0.60	63
4620	DQ	0.80	65
4620	RH	0.85	65
4626	DQ	0.85	65
4817	DQ	0.70	65
4817 (+0.23% Cr)	DQ	0.70	65
5 Ni-0.25 Mo (SAE EX-1)	DQ	0.70	63
8620	DQ	0.90	65
8620	RH	0.87	65
9310	DQ	0.80	63.5
9310	RH	0.80	65

tempered to reduce the brittleness and toughen the steel, since quenched martensite is hard, but also brittle. Tempering through hardened parts is generally done at 400 to 1000°F (205 to 450°C) for a period of one or more hours, depending on the size of the gear. Higher tempering temperatures increase the toughness, but also lower the hardness.

Limits on the Process. The quench and temper process is limited only by the size of furnaces and quench tanks available. Today, this is as large as several meters. From a practical standpoint, the major limitation comes from the ability to quench gears fast enough to obtain an acceptable microstructure. In some cases, particularly with lean alloy steels, it is just impossible to quench large gears fast enough to obtain an acceptable microstructure.

Table 2 shows the comparison of time required to achieve different levels of metallurgical quality between AISI 4140, a lean alloy steel with poor hardenability, and AISI 4340, a rich alloy steel. In order to compare the hardenability of a material, end quench (Jominy) values are widely used as an indicator of a steel's hardenability.

Since the quench is so critical to the resulting microstructure, it is necessary to verify the results with an appropriate sample. Too often a test coupon is used which is quite small as compared to the gear's sections. The small coupon is rapidly quenched, producing good results, while the cooling rate in the actual part is too slow and produces a poor result. (and this is where it needs to be good).

Carburizing

As mentioned above, the alloying elements in a steel have an effect on the hardenability of the material. In earlier years, it was known that increasing the hardness of the material increased the strength of the gear. This relationship held true up to a hardness of about 40 HRC. At hardnesses above this level, the material become brittle and the gears failed in breakage faster than gears with lower hardnesses. The idea behind case hardening is to keep the core of the tooth at a level which would not be too much beyond 40 HRC, to avoid tooth breakage, but to harden the outer surface, or "case," to increase pitting resistance.

Of the methods for case hardening gears, carburizing is the process which is most often used. The idea behind carburizing is to start with a gear blank which has a low amount of carbon in the base material, and then to add carbon to the outer surface. A properly carburized gear will handle between 30 and 50% more load than a through hardened gear. Case hardening is done primarily to *increase the pitting resistance of tooth surface.* However, because of the residual compressive stress which is present in the case after carburizing, there is also an increase in bending strength.

The Process. Carburized gears achieve hardness by quenching as do through hardened gears. The difference is that a carburized gear has an increased amount of carbon in the surface, causing this area to become a hard case after quenching, while the lower carbon core reaches a lower hardness.

Carburizing steels are alloy steels with approximately 10 to 20 points of carbon. The process involves heating the gears to a relatively high temperature and then rapidly quenching to obtain the hardness. This heating and quenching will result in distortion of the gear blank. The amount of distortion will depend on the mass and configuration of the gear and can vary from a slight amount to so much that the gear must be scrapped. Since the hard case is relatively thin, grinding to restore tooth accuracy may be so deep on one tooth side that the remaining case is too thin.

Due to the propensity to distort, it is recommended to stress relieve the gear blank before machining and, possibly, again one or more times before carburizing. In really critical jobs, it may be necessary to put the blanks through a "mock" carburizing cycle. A mock carburizing cycle exposes the blank to the temperatures and cycles it will see, and the blank still remains machinable, since no diffusion of carbon takes place.

The actual carburizing is done by heating the gear blanks to above the critical temperature and exposing the surfaces to carbon. The carbon can be a solid, liquid, or gas. As most carburizing is gas carburizing, the discussion here deals with this method. The carburizing is done in a furnace which contains a carbon atmosphere, such as natural gas. Above the critical temperature, the carbon diffuses into the material on the surface. The amount of carbon in the atmosphere must be controlled. Too much will cause carbide networks to form at the tooth tips and too little will produce shallow case depths, particularly in the root areas. The amount is measured in terms of percent and is referred to as the carbon potential. The optimum carbon potential which leads to the highest surface hardness will vary, depending on the alloy being used. Table 3 shows the carbon potentials which give the optimum results for several alloy steels.

When very deep cases are needed, the carbon potential is held at a slightly higher level (up to 1.1% carbon) in an initial portion of the carburizing cycle to give a boost to the diffusion.

The temperature in the furnace, the time in the furnace, and the carbon potential are variables which have an impact on the case depth. The alloy content does not have an influence on carbon diffusion. Fig. 1 is a chart showing the relation between temperature and time and case depth.

It is possible to directly quench parts from the carburizing temperature. This method minimizes the distortion, but does not result in a microstructure which is capable of long life (10^8 to 10^9 cycles). The case often contains excessive carbides and retained austenite. The core structure is unrefined. This method is used in the automotive field, since automotive gears rarely see more than 10^8 cycles. Also, since the production is high, and the facilities and tooling used for automotive gearing are highly developed, it is possible to obtain acceptable results.

Applications which require a high level of material quality are cooled and then reheated prior to quenching. In some cases it is also necessary to deep freeze the gears so that transformation to martensite is complete.

Limits to the Process. When the specifications are correctly chosen by the engineer and properly achieved by the heat treater, a carburized gear will be able to resist pitting and also have good bending strength. In order to achieve this capability, three things need to be in good order: 1) The surface and core hardness need to be correct; 2) The case depth needs to be deep enough in two areas and not too deep in one other place; and 3) the microstructure needs to be good enough for the level of loading.

1. Hardness. The required surface and core hardness should be selected based on the application. Depending on the alloy used, the hardness can be as high as 760 KHN (62 HRC). Long life power gears which see high loads for something like 10^9 to 10^{10} cycles need to be up to about 730 KHN (60 HRC), and the core hardness should be in the range of 360 to 400 KHN (35 to 40 HRC). Gears which are subjected to shock loading and do not see too many cycles may be better off with a surface hardness which has been tempered back to 55 HRC in order to gain more toughness.

Once the desired hardness has been determined, the drawing or specifications need to be specific as to what is required.[4] For instance, when hardness is checked on a mounted tooth sample, it is typically checked by taking a microhardness traverse. The microhardness is taken either by Knoop, a method using a 500- or 1000-gram load, or sometimes Vickers, using a kg load. Yet nearly all drawings specify surface and core hardness in values of Rockwell "C", a method which uses a 150 kg load. For this reason, a conversion must be made from either the Knoop number or the Vickers number to determine whether the part met the specified Rockwell number. Conversion is not simply a mathematical relationship. Since the structure and cold working properties vary for different materials and hardnesses,

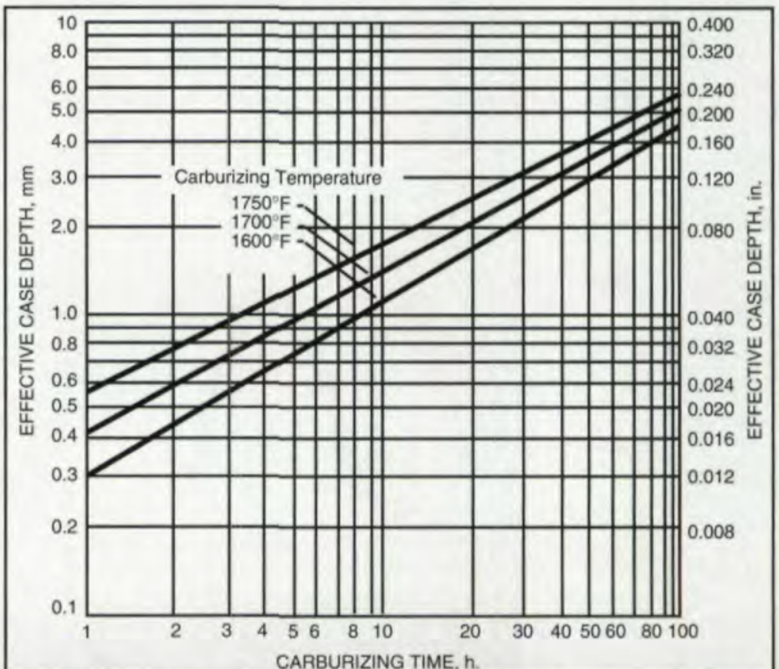


Fig. 1 - Nominal time and temperature requirements for different case depths.

The 150 kg load used for a Rockwell "C" check is inappropriate to check the hardness close to the surface or elsewhere in the case. This is because the size of the indention made by the 150 kg load homogenizes the conditions over a large area. This can mask local deficiencies.

Since it is appropriate to check a part with a microhardness method, the drawing and specifications should state the hardness number terms of a microhardness method. The equivalent Rockwell value could also be noted on the drawing for reference. An example of what is meant is shown below:

Case Hardness: 58-62 HRC
(Poor Practice)

Case Hardness: 690-776 KHN (58-62 HRC, ref)
(Good Practice)

2. Case Depth. Fig. 2 shows the shape of a typical carburized case. Note that the thickness at the tip is thicker than the case at the pitch diameter, while the case at the root fillet is thinner than at the pitch diameter. Though this shape is typical, most drawings only specify one value for case depth. Many drawings also fail to be clear as to how the case depth should be determined.

The effective case depth is usually defined as the depth of hardness to 50 HRC. Since there is room for misunderstanding this statement, a microhardness value similar to the one below would also appear on the drawing of specification:

Effective Case Depth: Determined by 542 KHN cutoff point (50 HRC, ref.)

The case depth at the pitch line (and in the dedendum just below the pitch line) is critical, since this area is most susceptible to pitting. The case depth should be deep enough for the case-to-core interface to be deep enough to avoid cracking due to subsurface shear stresses. The depth of case needs to be determined by the transmitted load and not by any relationship to the diametral pitch. A minimum value of case depth at the pitch line can be determined from the following relationship, which is based on the Hertzian band width:

$$h_{ec} = \frac{s_c d \sin o_t m_g/(m_g + 1)}{7.0 \times 10^8 \cos u_b}$$

where,

s_c = maximum contact stress in the region of 106 - 107 cycles

d = pinion pitch diameter, in.

o_t = pressure angle, transverse

u_b = base helix angle

m_G = tooth ratio

For situations where the ratio is high and the lowest point of single tooth is deep in the dedendum, the case depth may also need to be specified at a point in this region.

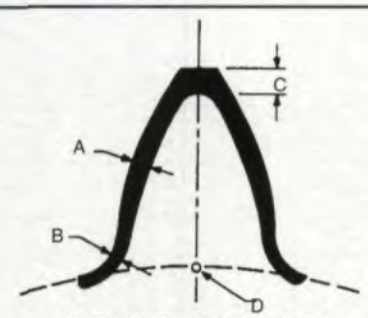
As mentioned above, carburized gear teeth gain in bending stress because of the residual stress in the case. This gain can only be realized if the case depth in the critical bending area near the root is deep enough. A minimum value for this case depth can be based on the diametral pitch, since the bending stress is related to the tooth size. If the teeth are sized properly for bending stress, then the following relationship should be valid for effective case in the root:

$$h_{et} = 0.6/\text{normal diametral pitch}$$

Such a value should appear on the drawing.

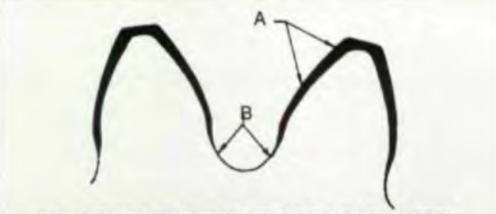
Many gears used today are operating at pressure angles of 22.5 to 25° Also, it is very common for designs to make the pinion "long addendum." Though there are many advantages to these tooth forms, the drawback is that this tends to make the top land quite narrow. To avoid the risk of tooth tips breaking off, the maximum case depth at the tooth tip should be limited to .40 divided by the normal diametral pitch.

Getting the case depth right at all these points becomes unmanageable when the teeth are very small. Twenty-pitch teeth are difficult and 28-pitch is the practical limit. With extreme care, finer pitches can be done. The difficulty in getting the case depth right on small gears is that the portion of time in the carburizing cycle during which the temperature is not stable (coming up to temperature and cooling) is large, compared to the overall cycle. Since the temperature is a variable affecting carbon diffusion, it is hard to



A FLANK CASE THICKNESS
B ROOT CASE THICKNESS
C TIP CASE THICKNESS
D CORE HARDNESS TAKEN HERE

Fig. 2 - Carburized case pattern. Shaded area is all 510 HV (50 HRC) or higher in hardness. Unshaded area is less than 510 HV (50 HRC).



A. TIP AND MID-FLANK HAVE GOOD CASE DEPTH.
B. ROOT FILLET AREA WITH ESSENTIALLY NO CASE.

Fig. 3 - Large carburized gear teeth having inadequate case depth in root fillet area because of heat soak back.

really know the amount of carbon entering the case during the heating and cooling portions of the cycle. Another variable, carbon potential, may not be set just right. On longer cycles, adjustments are made periodically to achieve good results. On short cycles, there is not much time to adjust if things are not just right in the beginning. Because of the number of variables, there is a very high possibility that something could go wrong.

The other problem comes from heat treating large gears. There is the obvious limitation in size due to the physical size of carburizing retorts and quench tanks. There is also a limitation which is more subtle. The transformation of the material to martensite during the quench is dependent on the cooling rate of the steel and its hardenability. When parts are large, it is extremely difficult to quench effectively enough to avoid heat soak back from the gear body. Soak back can prevent critical areas of the root from reaching the necessary hardness. Fig. 3 shows the case of a large tooth which suffered from heat soak back. The case depth at the pitch line was "as needed." A test bar with an appropriate diameter was used in the cycle. The case depth at the pitch line was in good agreement with the test bar; yet only a check on a tooth sample was able to reveal the actual problems.

3. Microstructure. Hardness alone is not enough to determine the strength of a gear. As was hinted above, hardness is only one of the properties that is determined by microstructure. In general, the microstructure is responsible for many of the important mechanical properties of a steel.

Fig. 4 shows some examples of the microstructure in a good carburized gear. Both case and core are relatively free of transformation products, and the structure of the base material is essentially tempered martensite.

Fig. 5, on the other hand, shows some undesirable microstructure variations. Although the case has a background of tempered martensite, there is a large percentage of transformation products in the structure. The core is in much worse condition, with the structure being almost all free ferrite and other undesirable transformation products.

It is important to realize that microstructure can vary from location to location within a gear. Because of this, it is imperative that the microstructure, along with hardness and case depth, be checked at several locations.

For case hardened gearing it is good practice to check the case microstructure at several places. It is recommended that this be done at the tooth tip, mid-tooth height, and the root fillet. These are the locations where microhardness traverses are done.

As mentioned above, core structure is generally studied near the root diameter and in the center of a tooth.

Nitriding

Nitriding, like other case hardening techniques, has the objective of increasing surface hardness of a given workpiece. Although nitriding is not suitable for all applications, it has proved to be a viable alternative in many manufacturing situations and deserves discussion.

Despite the fact that there are several nitriding methods available to the gear manufacturer, they all share the following characteristics:

•All nitriding processes require a source of nitrogen and a method of dissociating nitrogen radicals (ions) from the source.

•All nitriding processes rely on the ability of nitrogen to form stable nitrides with the elements of the stock metal.

•Alloying elements, such as aluminum, chromium, vanadium, and molybdenum, in proper amounts, will tend to enhance the success of nitriding processes.

•All steels are nitrided below transformation temperatures, thus quenching is not required. Conventional gas nitriding occurs within the temperature range of 925-1050°F (495-565°C). Ionitriding occurs within the temperate range of 660-1075°F (350-580°C).

•Case hardness achieved during nitriding is dependent upon the core hardness achieved before nitriding. This is especially true for certain alloy steels like AISI 4340, a typical gear steel used for nitrided applications.

•Surface conditions, such as cleanliness, can have marked effects on the nitriding process.

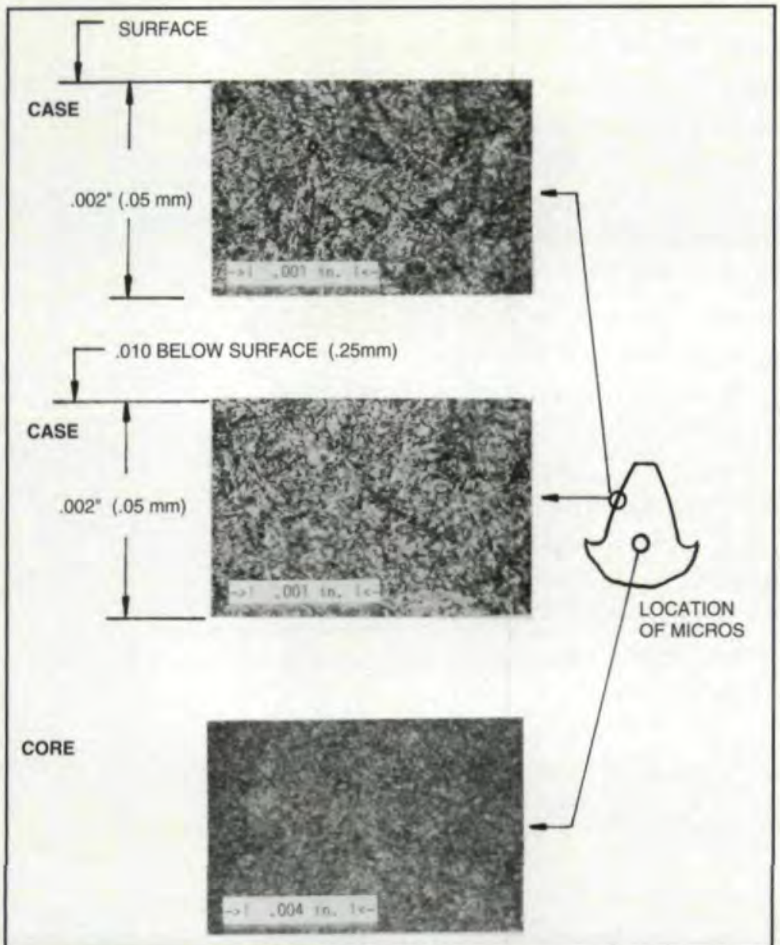


Fig. 4 - Desirable variations in carburized structure (case, core).

As is hinted above, there are many variables that can affect the success of the nitriding operation.

Although many steels can benefit from nitriding, including stainless types, much care should be taken when choosing a gear material. Certain steels are more suitable for nitrided application than others. Nitrides formed with various alloying elements tend to differ in mechanical properties, and the complexity of the situation is such that experience is often the only useful guide. Typical gear steels that are nitrided successfully are shown in Table 4.

After a good material choice has been made, pre-nitride heat treatment is the next step to assure the success of nitriding processes. Hardening and tempering is essential for all hardenable steels, and this relates to the dependence of case hardness on core hardness and microstructure.

The general recommendation is that the steel be treated to the condition of tempered martensite and that the tempering temperature be at least 50°F (30°C) higher than the nitriding temperature.[5] This helps prevent loss of hardness and decarburization, which leads to case embrittlement.

Because nitriding processes typically take place below transformation temperatures, very little distortion occurs in comparison to other common case hardening processes. As a result, gears are usually cut to size before nitriding. Stress relieving of machined parts is usually recommended and surface cleanliness is always required. All scale from prior procedures should be removed before nitriding, and all parts should be degreased. Vapor degreasing is the most common method.

Of the various methods of nitriding, there are three important processes to consider. The first two are gas nitriding processes, and the third process, ion nitriding, is an extension of conventional gas nitriding procedures that utilizes plasma discharge technology. Although several other methods have been developed over the years, many have fallen into obsolescence due to use and/or production of toxic chemicals, such as cyanide.

The Processes

Gas Nitriding - Single & Double Stage Processes. Gas nitriding involves dissociation of a nitrogenous gas, such as anhydrous ammonia, to produce nitrogen ions which can diffuse into the surface of the workpiece. These ions, in turn, form complex nitrides as affected steel surfaces, thereby increasing surface hardness. The process can be accomplished in one or two stages.

A typical single stage process goes as follows:

1. Hardening and tempering and machining of gear blank in various orders.
2. Stress relieving of machined gear.
3. Cleaning of machined gear and other surface preparation if necessary. Other surface preparation can include roughing of finish-machined surfaces and mashing of surfaces that are not to be nitrided.
4. Insert gear in nitriding furnace, bring to nitriding temperature and nitride.
5. Cooling cycle.
6. Removal of masking and optional final machining process, depending on white layer requirements.

The gas nitride cycle time will vary depending on cycle parameters, such as flow rate, pressure, temperature, required case depth, and required case hardness.

Typical single stage gas nitriding processes take place at temperatures between 925-975°F (495-525°C). The ammonia will dissociate upon contact with the hot steel surfaces and recommended dissociation rates for the single stage process are between 15 and 30%. This process produces a brittle nitride compound layer at the case surface, and it is termed the "white layer" because it etches out white in a micrograph. Typical thicknesses of the white layer are below .001" (.025mm).

Because the white layer is a brittle structure, it is often required that its thickness be minimized.

Although one can grind the brittle white layer off after the nitriding process, this is a costly operation that is not always practical. There is no guarantee that grinding will be uniform (especially in the root fillet region) and, if it is, that the case will be uniform at different locations on the gear tooth. A tooth that has required hardness and case depth at the O.D. will not always have the required hardness and case depth at the form diameter or other locations. Grinding of a uniform amount of stock can lead to imbalance of the residual stress pattern. For these reasons, control of the white layer is a concern when nitriding gears.

The double stage gas nitriding process has the advantage of producing less white layer than the single stage process. It is also a more efficient process. The double stage process uses two nitriding cycles with the first being similar to the single stage process, except for duration. Normally the gear is first nitrided at a 15 to 30% dissociation rate for 4 to 12 hours. The second stage of nitriding then takes place at a temperature equal to or greater than the first stage, but with a dissociation rate of 80 to 85%. To get this dissociation rate an external dissociator is required. Some typical double stage cycles and achieved case hardnesses and depths are shown in Table 5.

Ionitriding. Ionitriding, as mentioned above, is an extension of conventional gas nitriding which uses the methods of plasma discharge physics to deliver nitrogen ions to the workpiece surface. The general method involves use of high voltage electric energy in a vacuum vessel containing nitrogen gas. The mechanism which cracks the nitrogen gas into monatomic nitrogen ions is similar to that which takes place in a fluorescent lamp. Electrical connections charge the workpiece and the nitriding vessel so that the workpiece becomes a cathode, and the vacuum vessel becomes an anode. Electrons accelerating towards the anode impact with the diatomic nitrogen gas and dissociate the gas into nitrogen ions. These ions, in turn, accelerate towards the cathode and since the cathode is the workpiece, the nitrogen ions actually impinge upon the workpiece.

Limits on the Process. The primary advantage that nitriding has over other case hardening techniques that involve quenching processes is the small comparative distortion of treated parts. Geometry and tolerances of certain gears make nitriding the only viable case hardening alternative. Ring gears and other gearing that have thin-walled sections that would distort too much during a quenching process are often nitrided. In addition, nitriding is used sometimes when the size of a gear makes quench distortion and the subsequent grinding problems unacceptable.

Reproducibility of the nitriding process is another advantage it has over other common case hardening methods. Given parts of identical geometry and similar metallurgical quality and using identical nitriding cycles, case depth, case hardness, and case composition will be comparable. In addition, parts between batches will distort in exactly the same way. This means that machining can be biased before nitriding to compensate for expected distortions.

Ionitriding rates are better in both amount of distortion and reproducibility than conventional gas nitriding. Much of this has to do with the degree to which each of these processes can be controlled. Conventional gas nitriding, though a very controllable process, does not lend itself as well to pro-

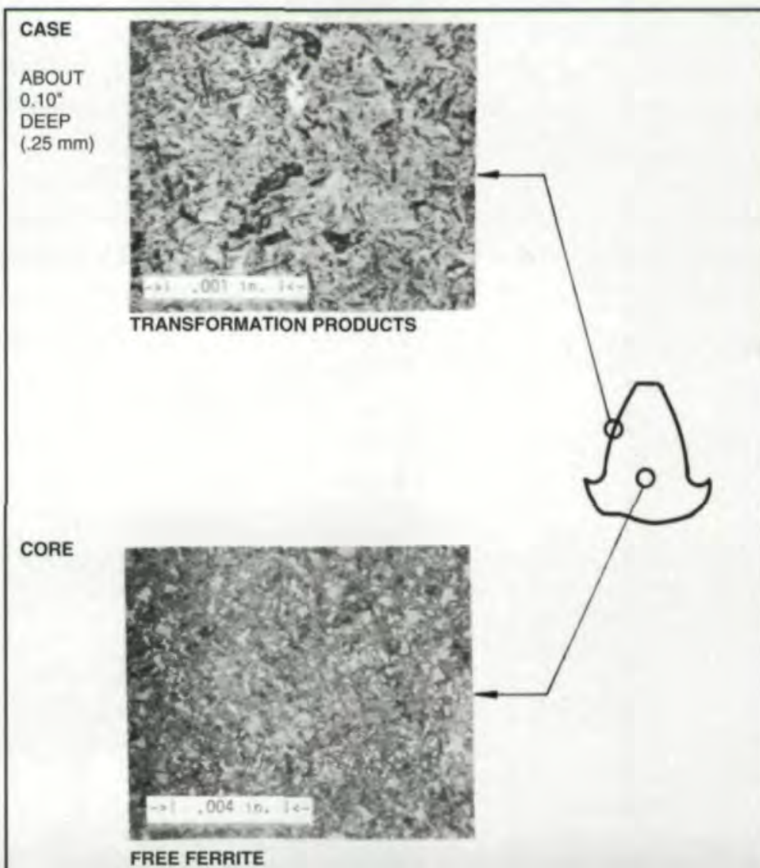


Fig. 5 - Undesirable carburized structure (case, core)

Table 4 - Common Nitriding Gear Steels

Steel	C	Mn	Si	Cr	Al	Mo	Ni
Nitralloy 135M	0.41	0.55	0.30	1.60	1.00	0.35	—
Nitralloy N	0.23	0.55	0.30	1.15	1.00	0.25	3.00
AISI 4340	0.40	0.70	0.30	0.80	—	0.25	1.83
AISI 4140	0.40	0.90	0.30	0.95	—	0.20	—
31 CrMoV 9	0.30	0.55	0.30	2.50	—	0.20	—

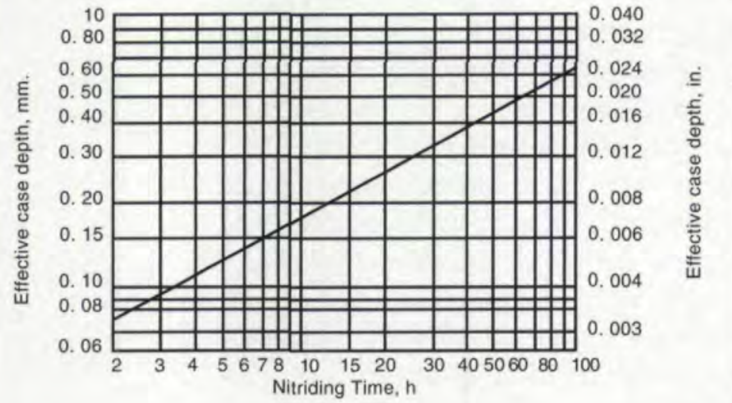


Fig. 6 - Nominal time required for different nitride case depths. Note: Under the most favorable conditions, about 40% more case depth is possible.

cess control. One example of this is the fact that the thickness and composition of the compound (white) layer can be successfully and repeatedly controlled when ionitriding. One even has the option of requiring no white layer. As controversy exists over whether the brittle compound layer is an initiation site for cracking, this is an attractive option.

Of the disadvantages of the nitriding process, the main one is that it takes much longer than other common case hardening techniques. The diffusion rate being exponentially dependent on temperature, nitriding takes place much slower than typical case carburizing or induction hardening procedures. The unpleasant side effect of this time dependence is that practical nitrided case depths are shallower than other case depths. Fig. 6 is a chart showing typical nominal gas nitriding times for different case depths.

Other disadvantages include the dependence on and sensitivity of the achievable case hardness to the metallurgy of the base material, and the tendency of nitrided cases to be less ductile than other cases. Lower case hardnesses and less ductility, in general, result in lower allowable stresses for nitrided gears.

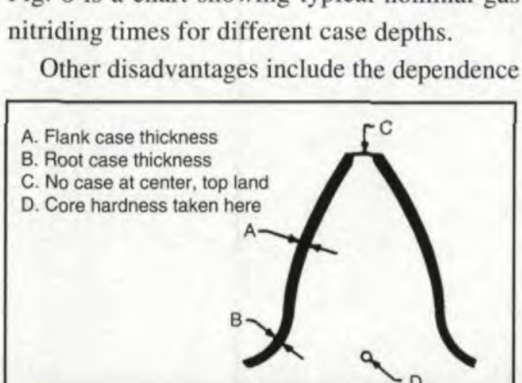


Fig. 7 - Induction hardened case pattern by the *scanning method of tooth heating.*

Carbonitriding (Gaseous). Carbonitriding as a process is related to both carburizing and nitriding. Typically carried out within the temperature range of 1550 to 1650°F (845-900°C), carbonitriding utilizes temperatures above transformation temperatures. Diffusion of carbon from a carbonaceous atmosphere is part of the process as well. However, like nitriding, diffusion of nitrogen is also involved. This is usually accomplished by addition of anhydrous ammonia to the carbon atmosphere.

The advantages of this process are related to the fact that it is essentially a compromise between the two parent processes. Taking place at lower temperatures than straight carburizing, the process has reduced distortion. Having a more favorable diffusion rate, the process produces a case faster than straight nitriding.

Carbonitriding is used for small gears with finer pitches than could be controllably carburized.

Induction Hardening. Induction hardening is a heat treating process which uses alternating current to heat the surfaces of a gear tooth. The area is then quenched resulting in an increase in hardness of the heated area. The hardness pattern which is achieved varies, depending on the type and shape of the inductor. An inductor which is circumferential will harden the teeth from the tips downward. While this pattern may be acceptable for splines and some gearing, heavily loaded gears need a hardness pattern which is more like a carburized case. This type of induction hardening is known as contour hardening. A typical case for a contour induction hardened tooth is shown in Fig. 7. Also shown in this figure are the three critical places to check the case on an induction hardened part. The discussion in this section deals with gears which are hardened by this method.

Since the area below the surface remains cool, it acts as a fixture minimizing distortion. In order to achieve high surface hardness, an induction hardening material usually has from 40 to 50 points of carbon. The resulting surface hardness is generally 53 to 58 HRC. The core hardness is developed by quenching and tempering the blank prior to the induction hardening.

Table 5 - Typical Double Stage Gas Nitriding Cycles					
Steel	Cycle	Effective Case Depth (Rc 50)	Maximum White Layer	Minimum Surface Hardness	Core Hardness
Nitralloy 135M	10 hr @ 975°F 28% diss. 50 hr @ 1026°F 84% diss.	.018"	.0007"	Rc 62-65	Rc 32-36
Nitralloy N	10 hr @ 975°F 28% diss. 50 hr @ 975°F 84% diss.	.014"	.0007"	Rc 62-65	Rc 38-44
AISI 4140	10 hr @ 975°F 28% diss. 50 hr @ 975°F 84% diss.	.025" etched	.0007"	Rc 49-54	Rc 27-35
AISI 4340	10 hr @ 975°F 28% diss. 50 hr @ 975°F 84% diss.	.025" etched	.0007"	Rc 48-53	Rc 27-35

By heating the outside layers the material tries to expand while being restrained by the inner material. As this layer cools, there is an increase in volume due to the increased hardness. The result, if properly done, is an outer case with residual compressive stress at the surface. The case-core interface is a critical area on induction hardened gears. If not properly done, this area is susceptible to cracking. In this region, there are high residual stresses due to drastic differences of the case and core structures and the fact that the transition occurs in a very short distance. (See Fig. 8.)

Induction hardening is done primarily to increase the pitting resistance of a gear. Though the load carrying capacity of induction hardened gearing is not as high as the best carburized gears, it is still quite high. And, in addition, this process does have some advantages over carburizing, such as less distortion on particularly thin-rimmed internal gears.

The Process. Through hardening materials are used for induction hardened gears. The same comments on hardness and hardenability as were made in the through hardening section apply here. Simply put, the amount of carbon in the material determines the achievable hardness and the alloy content determines the hardenability. This leads to the same conclusion reached in the through hardening section; that is, if high surface hardness and a deep case are required, a rich alloy steel with an adequate carbon content is needed.

As with through hardening, the teeth can be cut either prior to or after the quench and temper cycle which develops the core properties.

When a gear is carburized, it is said to go through one complete heat treat cycle, while a gear which is induction hardened is said to go through a number of heat treat cycles equal to three times the number of teeth. The inductor scans one tooth slot at a time and, because the heat treating conditions are different at the tooth ends than in the middle, it can be said that three heat treatments occur per tooth. One heat treatment occurs as the inductor enters the tooth slot, one occurs across the middle of the slot, and a third as the inductor passes off the tooth. Therefore, the more teeth there are, the greater the complexity of the job.

The case depth is a function of the power and speed of the inductor travel. It is difficult to verify the case depth on an induction hardened part without sectioning an actual part. Checking on the end is not practical because the case depth on the tooth end is usually not as deep as in the center area to prevent heat damage on the ends.

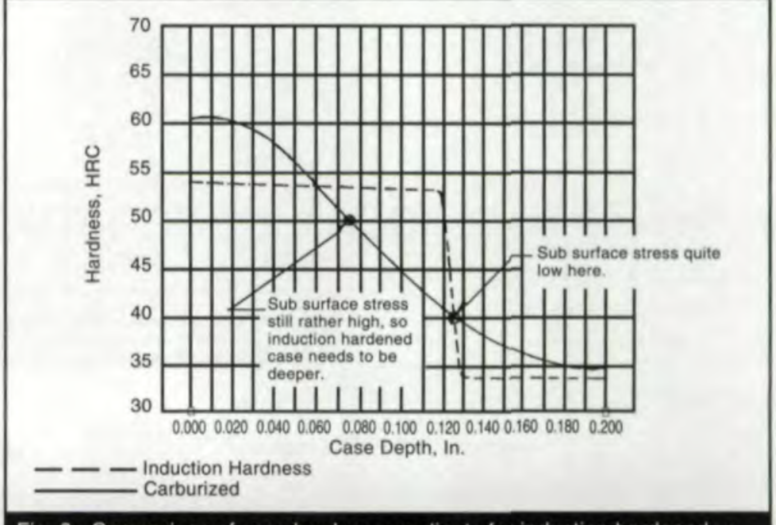


Fig. 8 - Comparison of case hardness gradients for induction hardened vs. carburized gear teeth.

It is usually necessary to grind induction hardened gears after hardening to restore the required accuracy.

Limits to the Process. Induction hardening becomes attractive as a process when the gears start to get large enough that carburizing becomes difficult; that is, when either the mass of the gear makes an effective quench impossible, or the shape of the part is such that the overall distortion is untenable. The teeth also need to be about 10-pitch or larger in order for an inductor to fit in the tooth slot.

Induction hardened teeth generally need more case than do carburized gears which are subject to identical loads. In order for a gear to resist pitting, the strength of the material in the case needs to exceed the stress which it sees. The shape of a curve of subsurface shear stress as plotted against depth is similar to the hardness-versus-depth plot of a carburized case. This means if the carburizing is done properly, the level of subsurface shear drops off faster than the material hardness. The drastic drop off of material strength on an induction hardened tooth may result in a drop off in hardness ahead of a drop off of stress. As mentioned, this area is subject to cracking. The results would be drastic. To avoid these problems, a deeper case is then specified. (See Fig. 8.)

Summary and Conclusions

Heat treating is a subject of great complexity and depth, and an in-depth discussion of all processes in current use is beyond the scope of this article. The general points covered are as follows:

•There is a wide variety of heat treatment processes available because there is a correspondingly large number of specialized needs.

•Often choosing the proper heat treatment requires assessing all the trade-offs.

•Sometimes, only one process will satisfy a particular application.

•The gear designer and manufacturer need to be cognizant of when a heat treatment is appropriate and when it is not. Understanding the capabilities and shortcomings of the common processes is necessary for such judgments.

Often the higher cost of a better material, better process, and a little bit of research can be substantially offset by savings in rejected parts and extra manufacturing steps. ■

Acknowledgement: *Presented at the AGMA 1991 Fall Technical Meeting. "1991, AGMA. Reprinted with permission.*

References:

1. ANSI/AGMA 2001-B88. "Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth." 1988.
2. ANSI/AGMA 2004-B89. "Gear Materials and Heat Treatment Manual." 1989.
3. AMERICAN SOCIETY FOR METALS. *Heat Treater's Guide: Standard Practices and Procedures for Steel.* ASM, 1982.
4. KERN, ROY F. "Achievable Carburizing Specifications." AGMA Technical Paper No. 88-FTM-1. 1988.
5. AMERICAN SOCIETY FOR METALS. *Metals Handbook: Vol. 4 Heat Treating.* 9th ed. ASM, 1981.
6. DUDLEY, D.W. *Handbook of Practical Gear Design.* McGraw-Hill, 1984.
7. HOWES, M.A.H. AND SHEEHAN, J.P. "The Effect of Composition and Microstructure on the Pitting Fatigue of Carburized Steel Cases." SAE 740222. 1974.
8. YOUNG, I.T. "A Wider Scope for Nitrided Gears." ASME 80-C2/DET-46, 1980.

Our Experts Discuss Hobbing Ridges, Crooked Gear Teeth, and Crown Shaving

Question: When cutting worm gears with multiple lead stock hobs we find the surface is "ridged". What can be done to eliminate this appearance or is it unavoidable?

Bill Janninck replies: We examined the sample worm gear you submitted as an example of the ridging problem. To illustrate it we show a scale graphical diagram of the gear tooth flank in Fig. 1. The lines on the flank show the ridges or high points on the profile surface representing a surplus of material. In the gear cutting trade the flats causing this are called generating flats and are similar to facets. These flats are a function of the number of flutes in the worm gear hob used in cutting the gear by the infeed process. In this process changes in feed or speed have no effect on the flats, as the hob and gear are locked together by the machine gearing. Unless the flutes in the hob are changed, these flats are unavoidable.

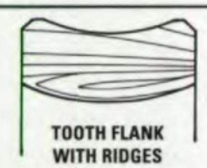


Fig. 1 Sketch of ridges on tooth flank.

In the hobbing process all parts cut, whether gears, splines, sprockets, serrations, etc., are formed by generating flats on the profile. Normally on finish-cut parts, the flats must be narrow enough to be inconspicuous and not cause a physical problem. This is easily accomplished using single-start or larger diameter hobs with more flutes.

We do not know the specific requirements for your gearing, but in most cases, if the flats are visible there may be a problem, both in smoothness of roll and in surface durability. On softer bronzes some ridging can be accepted with the peaks being smoothed down plastically in operation with the mating worm. But on the harder bronzes or with iron-based materials, such as yours, little ridging is tolerable.

Can one eliminate this appearance? Yes! The most direct and best way to do this is to use the tangential method of hobbing worm gears. Fig. 2 shows a comparison of infeed and tangential feed hobbing. The latter requires a special capability in the hobber which advances the hob axially at a rate which eliminates the ridges. Your current hob could probably be used in this mode.

Is this an expensive way to go? Yes! The infeed process is still the fastest way of cutting worm gears, and if one does not have a tangential hobber, there may not be much choice.

So let us ask another question. Could we improve the ridging using the infeed process? Yes! In your case the gear has 23 teeth and the hob has 4 starts. There are no common divisors in 4 and 23 so we have what is called a prime or hunting ratio. (If the numbers were 4 and 24, the ratio would be even or non-prime.)

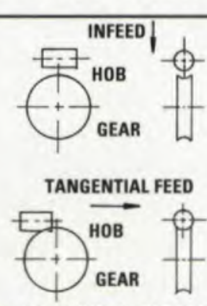


Fig. 2 Comparison of infeed and tangential feed hobbing.

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Address your gearing question to our panel of experts. Write to them care of Shop Floor, Gear Technology, P.O. Box 1426, Elk Grove Village, IL 60009, or call our editorial staff at (708) 437-6604.

William L. Janninck
does gear and tool design and consulting. He has been involved with gears and gear manufacturing for 45 years, 40 of them with Illinois Tools - ITW, Inc. He is the author of numerous articles on gear-related topics.

Don McVittie
is President of Gear Engineers, Inc., Seattle, WA. He is a past president of AGMA and Chairman of the U.S. Technical Advisory Group for International Gear Standards. He is a licensed professional engineer in the State of Washington.

With hob makers the usual rule is to make the flutes prime to the number of hob starts when the gear teeth and hob starts are prime. In your case the hob should have 9 flutes, which geometrically produce about 13 flats. We suspect your present hob has 10 flutes, and it will produce some 7 flats as was seen on the sample. Ten flutes in the hob with 4 starts have a common factor of 2, so one-half of the hob teeth will always track through the same path, reducing the possible flats generated by half. With 9 flutes there is no hob tooth tracking, and every tooth in the generating zone can cut a flat.

A single-thread hob is always prime, so all of the hob teeth available within the generating zone can cut. Hence, worm gears cut with single star hobs seldom have a problem.

SHOP FLOOR

Different rules for fluting are used for infeed and tangential feed hobs because of different geometrical needs, and the rules must sometimes be modified to suit available space for flutes in the hob blank.

The generating flat problem occurs more with low numbers of gear teeth, with higher numbers of hob starts, with lower pressure angles, and with higher hob lead angles. There are some parts with even ratios, such as the 4 and 24 mentioned above, where only tangential hobbing can do the job. There is definitely a place and need for tangential feed hobbing.

Question: We use a Gauthier hobber for cutting gears. What could be causing us to get crooked teeth on the parts cut?

Bill Janninck replies: It has been many years since I have heard anyone mention the Gauthier hobber. I believe it is of Swiss origin and is usually used to cut small gears of fine diametral pitch.

Usually a complaint of crooked teeth refers to what is seen in the plane of the profile. This crookedness, which some call lopsided or unsymmetrical teeth, can refer to involute or cycloidal form, but is more apparent on the latter.

This problem is not unique to the Gauthier machine, but is possible on all hobbers. The results are more obvious on small numbers of teeth and with the finer pitches.

There are several possible contributing factors which can be investigated. They include:

• *Hob wobble.* Hob wobble, which is a specific type of runout, can cause the hob teeth that finish-form that part to come into the cut out of proper position, and can cause an unsymmetrical form to be cut. The hob spindle can be checked for runout from end to end as a possible source for wobble. A bent spindle can be the cause of your trouble. But it is more important that the hob itself be checked while fully clamped down in the machine. The cantilever arbor used in some fine pitch hobbers is easily sprung if the nut face is not square.

•*Hob accuracy.* If the hob itself has been poorly formed or if the hob has been badly sharpened, the resulting errors can be directly transferred to the work.

•*The machine condition.* All machine parts are subject to wear or possible damage during routine use. In a gear hobber, the heart of the gear machine is the index drive worm and gear, and these have to examined particularly closely. If too much backlash or looseness exists, the part being cut can be randomly moving out of proper track, causing malformed teeth. Visual and mechanical inspection of the entire machine, including the gears, bearings, and ways, should be done.

To address questions to Mr. Janninck, circle Reader Service No. 78.

Question: We have a gear of the following dimensions: 28 teeth, 6 D.P., 20° P.A., Pitch Diameter, 4.666. It runs against a bull gear with the following dimensions: 67 teeth, 6 D.P., 20° P.A., pitch diameter 11.166. These gears are carburized to a minimum hardness of 58 RC. The case depth is .040-.045". The parts are solid disks with a hub on one side. The material is #8620, with no pre-machining heat treatment under our control (machined as purchased). These are spur gears. The lot size is 20 pieces, run once a month. They are quenched in open baskets, hub side down - no racking or controlled loading. Heat treatment is in-house. Distortion is a .015 to .030 "potato chip" measured on side of blank. There is heat treat distortion on the larger gear. We wish to correct this with crown shaving. Should the shaving be done on the larger or the smaller gear?

Don McVittie replies: The pinion is usually crown shaved, because it is smaller and because wide face solid pinions tend to distort in an "hourglass" form. The barrel-shaped crown that results from shaving tends to distort back to a more cylindrical form during heat treatment.

In many shops, shaving is cheaper than finish hobbing, improves finish, and makes a more accurate part. In that case, either or both gears can be crowned during the shaving operation.

Parts can also be tapered to compensate for conical distortion or shaft bending deflection. Crowning is also used to compensate for mounting problems, like variations in shaft alignment due to tolerances on bore locations and parallelism. The book, *Modern Methods of Gear Manufacture*, is no longer "modern", but it's still a good practical reference on gear shaving. The AGMA Gear Symposium to be held in Indianapolis on April 5-6 will also have discussions on both shaving and heat treatment.

The amount of crown is critical, since too much total crown in the pair of gears will concentrate the contact into a narrow area of the face and lead to premature pitting failures. A reasonable rule of thumb is "no more than .0003 to .0005" of crown per inch of face". (The tolerance is necessary to control shaving cost.) In other words, if only one member were crowned, the tooth thickness of a two-inch face width gear would be .0012 to .0020 less at the ends than in the center of the face.

This limits the amount of distortion which can be compensated by crowning. If the part distorts irregularly, if the distortion is more than .0003" per inch, or if the distortion varies much between parts, crowning won't be able to compensate enough to give good contact between the gear teeth. In that case distortion must be reduced by better heat treating practice or by a post-heat-treatment machining operation. Even post-heat-treatment grinding or hard cutting can have problems with badly distorted parts because of excessive stock removal on some teeth. Grinding steps in the root, shallow case depth, and excessive grinding times are examples of these difficulties.

The most likely areas for process improvement to reduce distortion are:

•Uniform pre-machining heat treatment and stress relief of the parts, so that the carburizing process doesn't act as a stress relief.

•Control of part loading and racking to assure uniform heating and cooling of all parts in each load. Each part in the rack should see the same heating and cooling rates. Crowded parts will be more likely to distort, since the quenchant can't flow uniformly between them.

•Slow, uniform heating, so that the thin sections of each part don't heat much faster than the thick sections.

•Slow, uniform, quenchant circulation. Dead spots in the quench medium will cause differential cooling, promoting distortion. Use the slowest quench which will give the required root hardness and microstructure.

•Part orientation during the quench to promote symmetrical cooling. Stem pinions usually quench better with their axes vertical, but some gears seem to do better with their axes horizontal.

It takes some experimentation to get the right recipe for each part. ■

To address questions to Mr. Mc Vittie, circle Reader Service No. 79.

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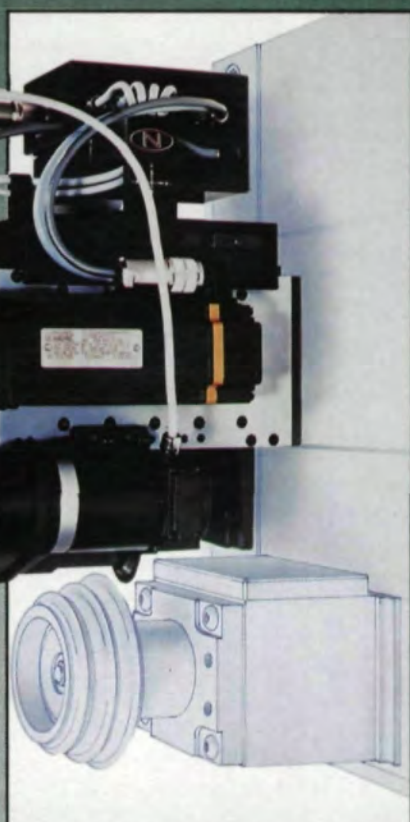

Made in U.S.A. Patent No. 4,559,919

ACCURATE

± .0001" (.002 mm) guaranteed!

VERSATILE

Dresses nearly any form in conventional or CBN grinding wheels.

DURABLE

Totally sealed and air purged, the FORMASTER is well suited to production environments.

EASY TO INSTALL

The FORMASTER'S compact design makes it easy to install on nearly any grinding machine, usually in less than a day.

EASY TO USE

Straightforward two axis programming can be learned quickly by production personnel. P.C. software is also available for generating involute gear profile programs.

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P.O. Box 69 • Arden, NC 28704
Phone (704) 684-1002 • Fax (704) 684-1384

NORMAC, INC.

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SAVE 20% ON GEAR COSTS

The size and weight of gear sets can now be reduced 20 to 50% by switching to the new Zero Transmission Error (ZTE) gearing, the first toothed gearing that has **no significant dynamic increment.** ZTE spur involute gear sets have much greater power density than conventional helical gears and **no significant whine or rattle at any speed or any load.** Specify the best, because it is also the least expensive.

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Rating Reviews, Testing (Gears, Contact Fatigue, Bending Fatigue, Wear), Problem Solving, Etc.
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- Able to match delivery to your needs
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- All services to AGMA standards

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fax 408-258-7335
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- ✔ Thermal Writing System for Fellows #4FPRL Red Liner
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. Mating form generation: racks, worms, gears on parallel or crossed axes—exact 3D math
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CALENDAR

MARCH 9-12

National Computer Graphics Association CAD & Engineering Workstations '92 Conference and Exhibition. Anaheim Convention Center, Anaheim, CA. Displays on CAD/CAM/CAE, product data management, solid modeling, rapid prototyping, and other engineering applications. Contact NCGA (703) 698-9600 or (800) 225-NCGA.

MARCH 17-18

SME's Bevel Gear Processing & Manufacturing Clinic. Livonia (Detroit), MI. Contact: Mike Traicoff, SME Headquarters, (313) 271-1500 x 596 or FAX (313) 271-2861.

APRIL 5-7

AGMA Gear Manufacturing Symposium. Airport Holiday Inn, Indianapolis, IN. Presentations on CNC Gear Shaping, Die Quenching, Heat Treating, Spiral Bevel Gears, Hobbing Fundamentals, and other subjects. Contact AGMA Headquarters: (703) 684-0211 or FAX (703) 684-0242.

APRIL 7-9

Engineering Society of Detroit's International Programmable Controls Conference & Exposition. Cobo Conference/Exposition Center, Detroit, MI. IPC is devoted to flexible automation and plant floor control. Contact: Tom Madeja, ESD Conferences, (313) 995-4440 or FAX (313) 663-7835.

APRIL 13-16

ASME-sponsored, CIME/design Computer-Integrated Manufacturing and Engineering Design Exposition and Conference. Cobo Conference/Exposition Center, Detroit, MI. Conference and show devoted to CAD/CAM/CAE/CIM. Call: Sharon Price, (800) 451-1196 or FAX (203) 666-4782.

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Max. Work Diameter	25"
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Machine Weight	32,500 lbs.

Whether your hobbing requirements are small or large, short or long, let Bourn & Koch's BEST FIT SOLUTIONS meet your needs and wants.

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The Polymer Composite Base with Hardened and Ground Ways, Power Hob Swivel with Automatic Clamp/Unclamp, Quick Change Hob Arbor with Hydraulic Nut, Power Tail Stock Bracket with Hydraulic Center, guaranteed the ANSI Class 5 Quality.

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CIRCLE A-21 on READER REPLY CARD

ADVANCED GEAR SHAVING MACHINE FOR GEARS UP TO 18-IN. DIAMETER

The GFF gives you next-generation high output and accuracy – new, or retrofitted from your model GCU.

Advanced controls, greater power and variable-speed drives yield important gains in productivity … as well as quality, control, and flexibility. Whether you elect to buy a new GFF or retrofit your GCU — conserving the highly-stable, C-shaped machine body — the advanced model design provides:

INCREASED PRODUCTIVITY:

REDUCED SET-UP TIME. The GFF is equipped with variable-speed AC servo motors that dramatically reduce set-up time (vs change gears and single-speed motors) for the cutter head speed, table infeed, and shaving table speeds. The addition of optional quick-change tooling and hydraulic cutter clamping significantly reduce change-over time.

OPTIMIZED CYCLE-TIMES. With the flexibility designed into the GFF, you can now select the exact speeds and feeds (even choose different settings for shave and dwell passes) to best balance part geometry and tool life considerations.

AUTOMATIC PIN SIZE COMPENSATION. The machine control can accept part inspection data via a standard RS-232 serial port. Based on this data, the control can automatically compensate the upfeed stroke in 0.0001 increments for variances in the parts' pin size.

EASE OF OPERATION:

MENU PROGRAMMING.

- Menu-style programming screens.
  - Easy-to-use, user-prompt menus.

  KEYING-IN INFORMATION.
  - Equipped with Allen Bradley's state-of-the-art Model PLC-5.
  - Man Machine Interface.
  - CRT screen control.

Permits operator to:

- Select cutter RPM and diagonal shaving table feed.
- View displays, such as the crossed axis setting of the cutterhead.
- All modes of operation — conventional, plunge, diagonal and underpass — are easily programmed through the control.

GREATER FLEXIBILITY:

VARIABLE-SPEED DRIVE.

- AC cutter head motor speeds from 50 to 500 RPM.
- AC servo motor for the diagonal shaving table feed.
- AC servo motor upfeed .004 IPM to 12 IPM.

ENHANCED QUALITY CONTROL:

MORE RESPONSIVE MOVEMENT.

- Vertical ways surfaced with a Teflon™-based compound, to reduce friction and ensure more responsive and smooth operation of the table upfeed.
- A pneumatic counter balance system improves sensitivity of the table upfeed ballscrew, and increases its service life.

THERMAL GROWTH COMPENSATION.

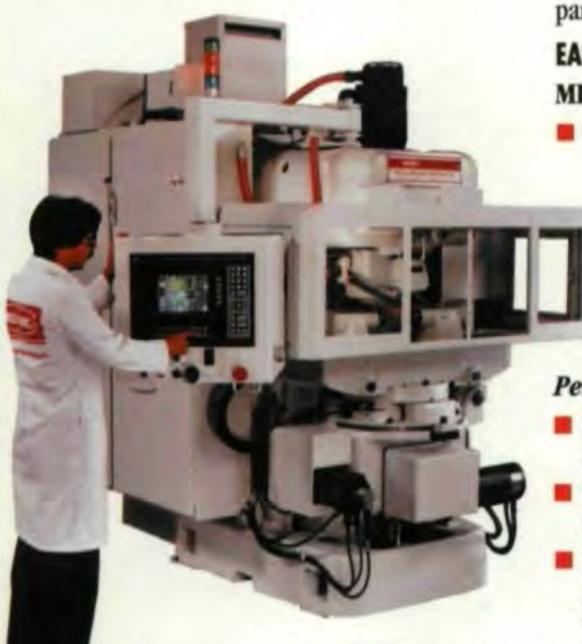
- Three thermistor feedback devices continually adjust the upfeed drive.

ACCURATE MONITORING.

- A 17-bit, high-resolution absolute position encoder provides accurate monitoring of the crossed axes setting of the cutter head.

PRECISE CONTROL OF TABLE TRAVERSE.

- Precision ballscrew and recirculating nut, plus encoder, offers greater control of the table stroke accuracy.



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