Specifying Custom Gears

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Gear design and specification are not one and the same. They are the first two steps in making a gear. The designer sits down and mathematically defines the gear tooth, working with the base pitch of the gear, the pressure angle he wants to employ, the number of teeth he wants, the lead, the tooth thickness, and the outside, form and root diameters. With these data, the designer can create a mathematical model of the gear. At this stage, he will also decide whether the gear will be made from existing cutting tools or whether new tools will be needed, what kind of materials he will use, and whether or not he will have the gear heat treated and finished.

That is the design end. The specifications are the data given to the manufacturer that permit him to properly make and test your gear. Here we are discussing the design drawing you submit as well as the information that should and should not be included. At this point in the process, any vagaries in your design, such as the effects of heat treating or finishing, should have already been resolved. When you are ready to write your specifications, you should be ready to make your gear.

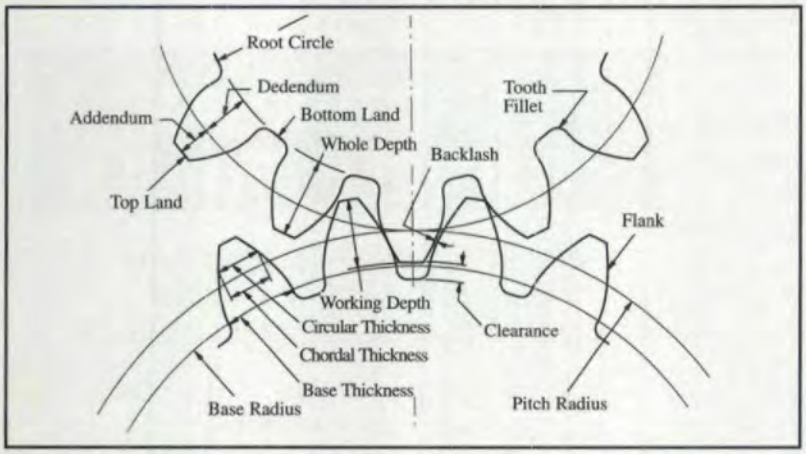

Fig. 1—Gear design nomenclature. Courtesy of Van Gerpen and Reece Engineering.

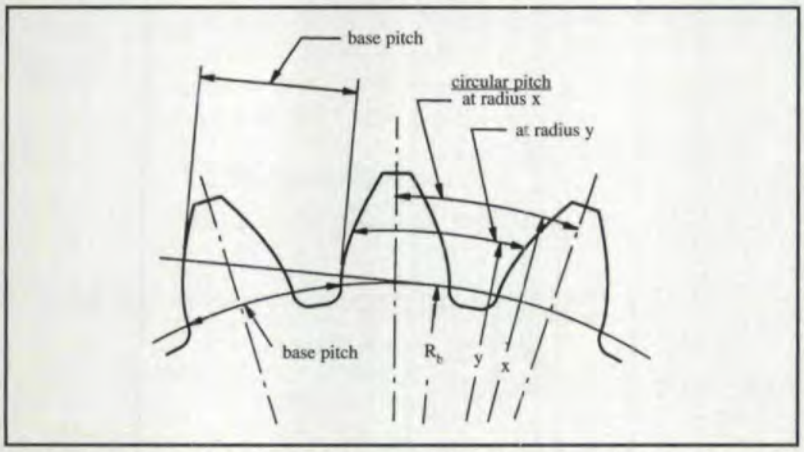

Fig. 2—Base pitch and circular pitch. Courtesy of Van Gerpen and Reece Engineering.

Designing Your Gear

Gears are usually designed from their cutters (hobs, shaper cutters, etc.) and, likewise, cutting tools are often designed from the specifications of the gears being made. If you create a new gear, it is possible that you will be able to use existing tools to manufacture it, but the odds are that you will want to create a new tool to handle the new design. The data you will need to accomplish this come from the basic design elements of the gear itself. All of the following parameters can be delineated in either metric (millimeters) or English (inches) units.

A word should be said about metric and English measurements. The global market today is primarily metric. The prevalence of English measurements in the United States is, for the most part, due to the vast number of cutting tools in the inventory that are already specified in inches. Since it is likely that you will have to convert your gear measurements to metric anyway, as long as you are going to design the tool as well as the gear, you will save yourself some work by designing the gear in metric to begin with.

Base Pitch. This is the base circle circumference divided by the number of teeth. It is a constant distance between each of the teeth along the line of action. The symbol for base pitch is P_b in both metric and English designs. The term *Normal Base Pitch* refers to the base pitch in the normal plane of an involute helical gear.

Pressure Angle. The angle, measured in degrees, between the line of pressure and the plane tangent to the pitch circle at the pitch point (the point of tangency between two pitch circles). The pressure angle is labeled α or α_t.

Number of Teeth. The number of teeth your gear has along its entire circumference. The symbol is z_2. In spur gears, this parameter is determined from the pitch diameter (D) and the diametral pitch (P) with the formula $N = D \times P$. For helical gears, the formula is $N = D \times P \times Cos(\beta)$ where β is the helix angle.

Lead and Hand of the Helix. Lead is a measurement of the axial advance of the helix for one complete turn. Hand is the direction of the turn, specified as either right or left. The lead symbol is p_z.

Helix Angle vs. Lead. Specify the lead of a gear rather than the helix angle because lead is a constant value while helix angle is not. Finding the helix angle depends upon knowing the diameter of the circle associated with the angle.

Tooth Thickness. The arc thickness of the tooth at a given radius from the mounting center of the gear. As a specification, this measurement is also referred to as ***circular tooth radius***. The metric symbol for tooth thickness is s. In English units it is t. To mathematically find the normal tooth thickness in a standard spur gear, use the diametral pitch (P) in the formula $t_t = 1.5708/P$. For the normal tooth thickness in a helical gear, use the normal tooth thickness ($t_n = 1.5708/P_n$ where P_n is the normal circular pitch and is found with $P_n = P/cos\beta$) and the helix angle in the formula $t_t = t_n/cos\beta$. Because rack shaped cutters (i.e. hobs) operate in the normal plane, the transverse diametral pitch is not usually specified as it tends to confuse things.

There are several ways of directly measuring tooth thickness. These include tooth calipers that measure chordal thickness at a given radius; span micrometers, which measure the distance across several teeth; center distance with a master gear; and dimensions over balls, pins or wires, which gives you a dimension over two balls placed in opposing tooth spaces. The problems associated with specifying tooth thickness based on any one of these methods are the implication that this is the only viable method for checking the gear, the usually false belief that the balls will measure the tooth thickness at the nominal pitch circle, and the need to recalculate the tolerance on the dimension over balls when changing the size of the ball. How these difficulties are eliminated by adopting the convention of specifying circular tooth thickness as normal tooth thickness measured at the base circle will be discussed in the specifications section.

Outside Diameter. This is defined as the diameter of the addendum circle. In bevel or

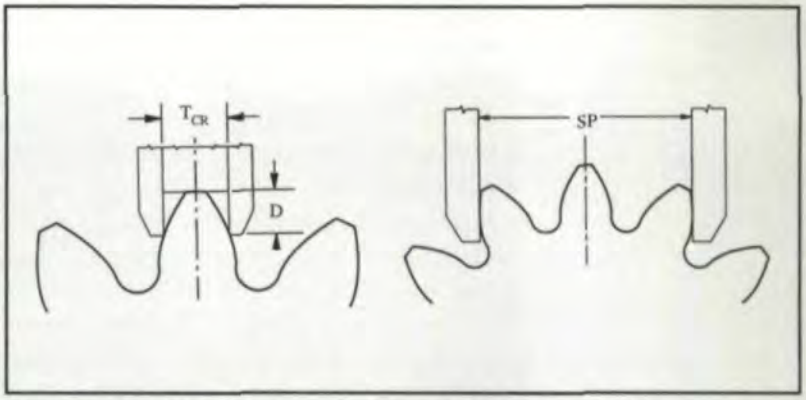

Fig. 3a—Tooth calipers. Courtesy of Van Gerpen and Reece Engineering.
Fig. 3b—Span Micrometer. Courtesy of Van Gerpen and Reece Engineering.

hypoid gearing, however, the O.D. is the diameter of the crown circle. In metric gear designs, the symbol for outside diameter is d_{a2} and in English designs it is D_o. In spur and helical gears, the outside diameter can be found using pitch diameter (D) and addendum (a) in the formula $D_o = D + 2a$. In straight and spiral bevel gears, the formula uses pitch diameter (D), the addendum (a) and the pitch angle (Γ) of the gear. The formula is $D_o = D + 2a_{oG} \cos \Gamma$. The pitch angle of the gear is determined from the pitch angle of the pinion with the formula $\Gamma = 90° - \gamma (\Gamma = tan^{-1} z/Z$, where z is the number of teeth on the pinion and Z is the number of teeth on the gear).

Form Diameter. This is the diameter of the circle intersecting the trochoid formed by the cutting tool and the involute tooth profile. It is also the limit of tooth contact between mating gears. The symbol is $d'f$.

Root Diameter. This is the diameter of the root circle. When considering bevel gears, it is the diameter of the root circle at the outside ends of the teeth. The symbol is d_{f2}. In spur gears, root diameter can be determined by $d_{f2} = D - 2b$ (where b = dedendum and D = pitch diameter). In a worm, the formula is $d_{f2} = d_o - 2h_t$ (where d_o is the outside diameter of the pinion and h_t is the whole depth of tooth).

These various design elements will allow you to define your gear mathematically. They will either appear as, or be used to get, the specifications that will appear on your drawings to guide the manufacturer in the creation of the cutting tool needed to make the gear.

Other Useful Design Elements

You will need to specify other things about your gear that, while not directly related to the design of the cutting tool, will have a great impact on the manufacture of your gear.

Topland Width. Topland is the thickness of the top of the tooth as measured in the direction

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of rotation. Topland width measures the same surface perpendicular to the direction of rotation. It is, therefore, a measurement of how thick the gear teeth will be. This is important because the designer has to guard against the topland width approaching zero.

Backlash. Measured on the operating pitch circle, backlash is the amount of space between mating teeth in a gear pair when the driving tooth is in contact with the driven tooth. All gear pairs must have backlash if they are to operate properly. When you are designing your gear, you must consider runout and center distance tolerances as these will cause variance in the circular pitch at the operating pitch circle, and that is the parameter you use to determine backlash. As a rule of thumb, you can determine backlash for a given pitch as follows: 0.030 to 0.050 inches divided by the diametral pitch. For example, a 3 DP gearset would have a 0.010 to 0.017 inch backlash.

Contact Ratio. The ratio of the transverse arc of action to the transverse base pitch, this element is found by dividing the length of mesh along the line of contact by the transverse base pitch.

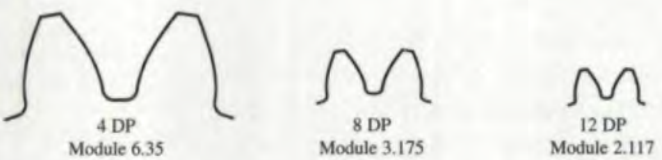

Fig. 4—Diametral Pitch and Module. Courtesy of Van Gerpen and Reece Engineering.

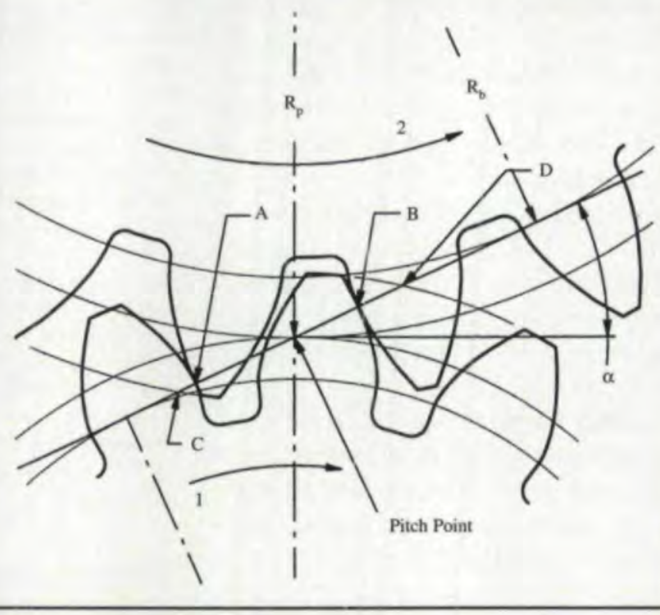

Fig. 5—Base tangent line. Courtesy of Van Gerpen and Reece Engineering.

Materials. The selection of materials is usually based on the type of application you are designing. According to Dudley's Gear Handbook: "The use of a specific gear material should be based on several factors, chief of which is the service application for which the component is designed. Other considerations for the use of a particular material would be material availability, raw stock cost, load-carrying capacity, environmental considerations such as corrosion—corrosion protection and manufacturing requirements."

Materials are divided into two categories: ferrous and nonferrous gear materials. Ferrous materials include all the various types and grades of iron and steel available. These are the most widely used gear materials today. They are cheap and can be heat treated to improve their hardness and increase their load capacity. Ferrous metals are used when strength, durability and safety are paramount.

Nonferrous gear materials include aluminum alloys, zinc alloys, bronzes, plastics, nonmetallic laminates and other, more exotic materials. They are often used when gears must be light weight, as in aerospace applications; or the load they will carry is minimal, as with computer printers and other light duty consumer applications. They are also useful in precision instruments where the inertia of turning gears must be minimal, when the gear's operating environment would be too hostile for iron or steel, or when low cost mass production is needed.

Post-Manufacture Processing. This includes the whole gambit of finishing procedures from grinding and honing to heat and cryogenic treatments. These procedures are performed to improve the surface characteristics of the gear in order to reduce or eliminate transmission errors that lead to noise and vibration. For example, honing has been shown to have a profound effect on the sound characteristics of the gear (see "An Experimental Study on the Effect of Power Honing on Gear Surface Topography," *Gear Technology*, January/February 1999).

Heat treatments of various kinds including flame hardening, induction hardening, carburizing, carbonitriding, nitriding and other procedures are used to harden and temper steel and certain kinds of iron by changing the chemical and/or grain structure to make them more resistant to wear, pitting and cracking.

Case Depth and Hardness. If you have chosen a ferrous metal gear for your application, you have to be concerned with case hardness and case depth, as these parameters affect the load capacity of your gear. Heat treatments that introduce carbon or nitrogen into the surface of a metal create a hardened shell, called a case, around a core of somewhat softer metal. Case depth is a measure of how thick that hardened shell is, while case hardness is a measure of how hard the shell is.

Hardness can be measured on any one of a variety of scales; however, Rockwell C hardness or Brinell Hardness Number (BHN) are the most prevalent. A steel with a 250 BHN is equivalent to a Rockwell C24 rating. This steel is soft, easy to cut, and has a moderate load capacity. A steel with a 610 BHN is equivalent to a Rockwell C58 rating. At this level of hardness, the gear would have to be ground, not cut, and would have a very high load capacity. It is not unusual after heat treatment for a gear to have a 250 BHN core and a 610 BHN case. The advantage of the case hardening process is that the core of softer material is much tougher and more ductile, with better bending fatigue strength, than the hardened but more brittle case, which has better pitting, cracking and load carrying properties.

Quality. This refers to the tightness of your design tolerances as well as to the standard by which you are going to measure your gear. Will you use AGMA, ISO, DIN or some other standard? What class within the standard are you trying to achieve? AGMA Class Q10 gears, for example, are machine cut and show a good level of precision with an achievable tolerance of 0.0125 mm to 0.05 mm. Q10 gears have far tighter tolerances than AGMA Class Q5, which are die cast, commercial quality gears with a tolerance range of 0.05 mm to 0.125 mm. AGMA Class Q14, however, are precision ground and have a tolerance range of 0.0025 mm to 0.0125 mm. Be aware that it is possible to have different quality levels with respect to alignment (lead), profile and runout.

You should also understand the relationship between heat treatment and quality levels. As a basic rule of thumb, you will lose at least two quality levels after heat treating. This means that a gear rated to AGMA Q10 before going through heat treatment will come out as an AGMA Q8 gear due to the distortions involved in heating and quenching the metal. This is important to know because you will have to decide whether to live with the lower quality or put the gear through a finishing process to get those lost quality levels back.

These parameters will round out your description of the gear itself. However, to get the complete picture, your designer or manufacturer will need to know something of the application itself. Specifically, he will need to understand the gearbox.

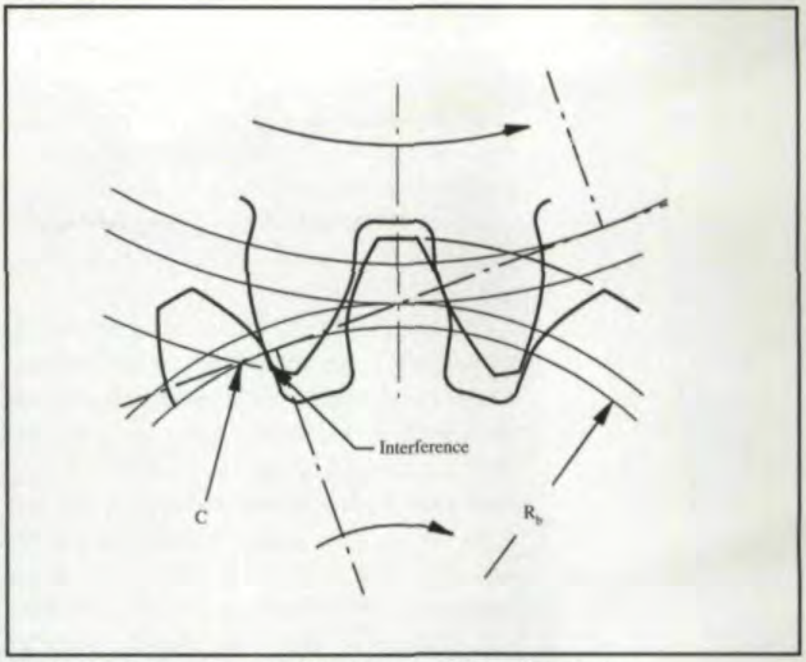

Fig. 6—Interference. Courtesy of Van Gerpen and Reece Engineering.

The Gearbox. Understanding how your gear is to interact with the other gears in the gearbox, and what kind of output you expect to get from that gearbox, is essential for good gear design. You will need to know the size of the gearbox as well as the width of the cavity in which the gear being designed will be installed. You should also know how many gears will be inside the gearbox, their configuration and the lubrication you are planning for. The speed you expect from both the gear itself and the gearbox as a whole, as well as the torque and turning force you expect to generate, are also important considerations.

Issues of Gear Specification

Specifying a gear for manufacture is a straightforward process once you have all the data the manufacturer will need to do the work. This is not the same as gear design, which is a process primarily focused on developing the tooth form, but it does use some of the same design elements you developed during the design stage. Specification is the next step, where your design parameters are put into action.

The real trick to gear specification is getting in all the necessary information while excluding everything else. The most common pieces of unnecessary information include part number and data regarding the mating gear, backlash with the mating gear (in spite of its importance in the design stage), cutting tool part numbers, dimension over specific wires or balls, and pitch circle diameter other than the base circle. Overspecifying your gear can mean that you don't know enough about involute gear design, that you are unnecessarily restricting the shop to certain tools and processes, or that there is a problem with double-dimensioning on the gear leading to uncertainty as to which measurements are correct.

There are only eight items required to properly specify a gear. Mentioned earlier are ***number of teeth***, ***circular tooth thickness***, and ***lead and hand of helix***. The other specifications, which are based on the design elements, are: ***base circle radius, outside radius, true involute form radius, root radius and face width***. By including these with your specification drawing, along with the tolerances on these dimensions, you will make sure your manufacturer has enough information to both produce and inspect your gear correctly.

Base Circle Radius. The easiest way to specify the base circle size of your gear is to use the untoleranced radius of the base circle. You can also specify the base circle radius mathematically using the module (the same as the normal diametral pitch) (m), the pressure angle (α_n), helix angle (β) and the number of teeth (Z) specified at the same point on the gear tooth. If you specify these values from different points on the tooth, you will make errors that will be hard to find and correct. Another problem arises if these values are provided along with the base circle diameter, as this often leads to confusion over which values to use. Assuming that you have all your values correct, the equation for finding the base circle radius is:

$$R_b = \frac{ZCos[Tan^{-1}(Tan\alpha_n/Cos\beta_g)]}{2mCos\beta_g}$$

Outside Radius. Also referred to as the ***addendum circle radius***, this value can either be determined from the ***outside diameter*** or by tracing a circle with a radius extending from the mounting center of the gear to the farthest point on a tooth. In specifying this parameter, be sure to give the maximum effective diameter as well as the minimum actual diameter.

True Involute Form Circle. This circle crosses the involute surface where the involute surface becomes usable. This surface must remain within tolerance from that point to the outside circle (or to some other specified form point). This parameter can be rendered as a radius, as degrees of involute roll to the form point, or as the length of the base tangent line to the form point (you need to know the length of the base tangent).

Root Radius. In order to prevent interference, the root radius must be specified. This parameter is measured from the center of rotation to the deepest point in the tooth fillet, or it can be developed from the root diameter mentioned above. It should be noted that if the clearance between the root circle and the mating gear tooth were allowed to be zero, then it would be possible for the corner of the mating tooth to interfere with the fillet between the root circle and the form circle.

Face Width. This is the length of the tooth in the plane (the axial direction) of spur, helical or herringbone gears, essentially the axial width of the gear. It is used to make the blank and to calculate stresses. You can find it by dividing the length of the teeth by the cosine of the helix angle:

$$F = \frac{T_L}{cos\beta}$$

Conclusions

There is other information which your designer or manufacturer will ask you to provide, other decisions to make, but they come later in the process. You must begin with the basics of your design and effectively communicate the geometry, materials, finishing, quality requirements and post-manufacturing processing of the gear, as well as the demands your application will place upon it, to your designer or manufacturer. Your ability to provide this information clearly and accurately will make the entire design and manufacturing process smoother right from the start.

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