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Introduction to Gear Design

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Introduction

Gears are wheel-like machine elements that have teeth uniformly spaced around the outer surface. Gears can be a fraction of an inch in diameter to a hundred feet in diameter. Gears are used in pairs and are a very valuable design tool. They are used in everything from clocks to rockets and have been around for 3000 years.

Gears are mounted on rotatable shafts and the teeth are made to mesh (engage) with a gear on another shaft. Gears deliver force (torque) and motion (rpm) from one part of a machine to another. Two gears with the driven gear having twice the number of teeth of the driving gear will rotate at one-half the speed of the driving gear and deliver twice the torque. Being able to control speed and torque by varying the number of teeth in one gear with respect to another makes gears a valuable design tool. An automobile transmission is an excellent example of how this principle is put to use to control vehicle motion.

Types of Gears

There are a number of different types of gears. Spur gears are the most common and the easiest to manufacture. A spur gear has teeth that are uniformly spaced around the outer surface. The teeth are aligned in a direction that is parallel to the gear axis of rotation. A spur gear is designed to mesh with another spur gear on a parallel shaft.

The profile of the contact surface of spur gear teeth is in the form of an involute curve. An involute curve is the path the end of a string takes when it is being unwound from a cylinder. The shape is the easiest to manufacture and is an efficient way to transmit power between two contacting surfaces because of the tendency to maximize rolling and minimize sliding. The efficiency of spur gears is in the high 90% range and approaches that of anti-friction bearings.

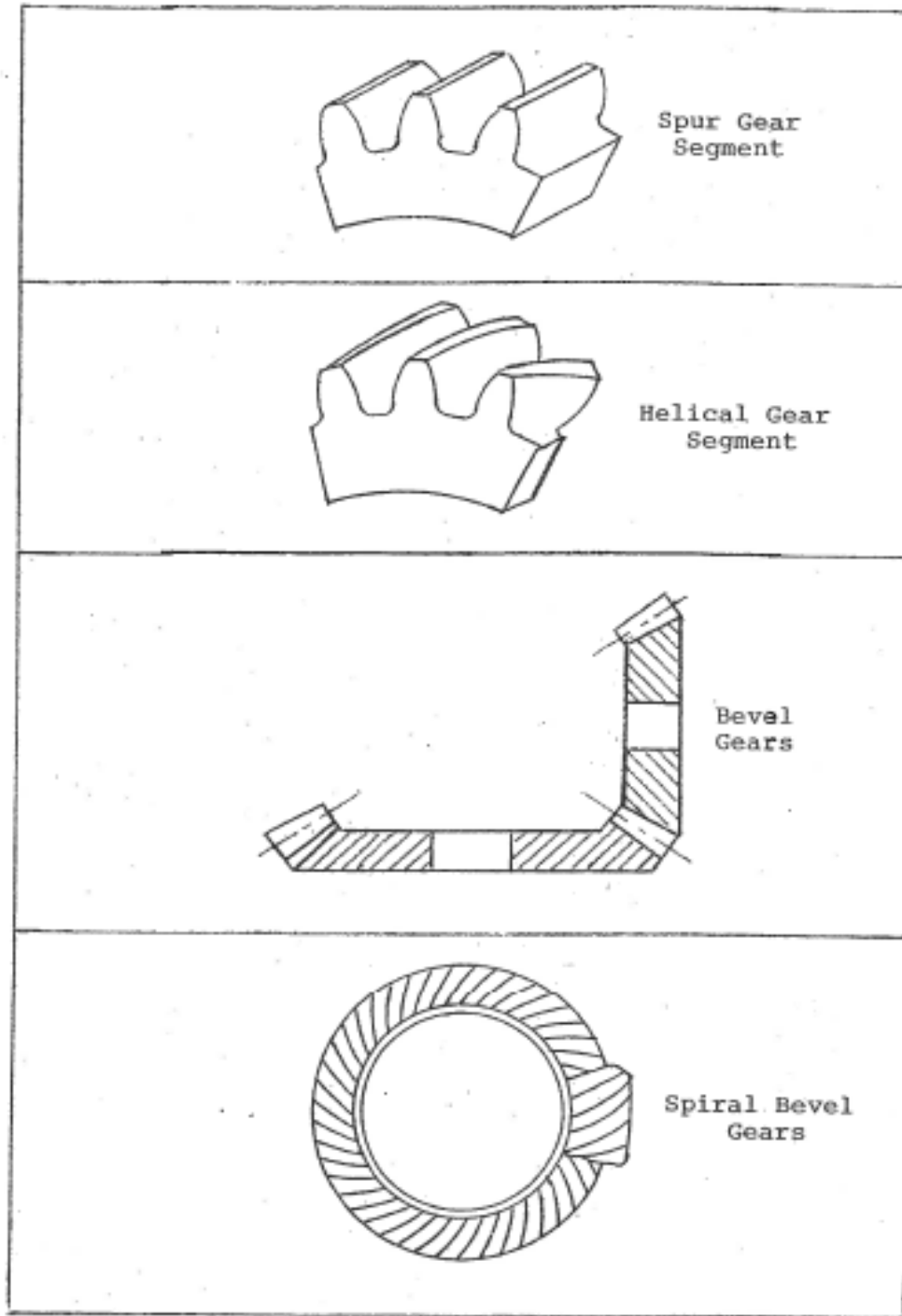
Spur gears impose only radial loads (perpendicular to axis of rotation) on shaft support bearings as opposed to other types of gears which impose radial and thrust loads (parallel to axis of rotation) on bearings. Gears that impose thrust as well as radial loads require shaft support bearings that are designed to support both types of loading.

Helical gears are like spur gears except that the teeth are positioned at an angle to the gear axis of rotation. This angle, called the helix angle, is normally from 10° to 35° . Helical gears are stronger and run more quietly than comparable size spur gears. Helical gears are less efficient than spur gears and impose thrust as well as radial loads on shafts making bearing and shaft selection more complex. Double helical or "herringbone" gears can deliver high power without imposing thrust loads on shafts.

Bevel gears are like spur gears except that the basic tooth configuration is conical in shape resulting in the teeth being smaller at one end than at the other. Bevel gears are used to transmit power between two shafts that are not parallel. Two shafts that are at a 90° angle to each other are commonly driven by bevel gears. Bevel gears, like spur gears, operate at efficiencies in the high 90% range. Bevel gears are used in vehicles, aircraft, and machine tools. Spiral bevel gears are cut at an angle similar

to what helical gears are to spur gears. Spiral bevel gears can deliver more power but operate at lower efficiencies than straight bevel gears. Spiral bevel gears whose axes do not intersect are called hypoid gears (explained later). See Figure 1.

Figure 1
Gear Types



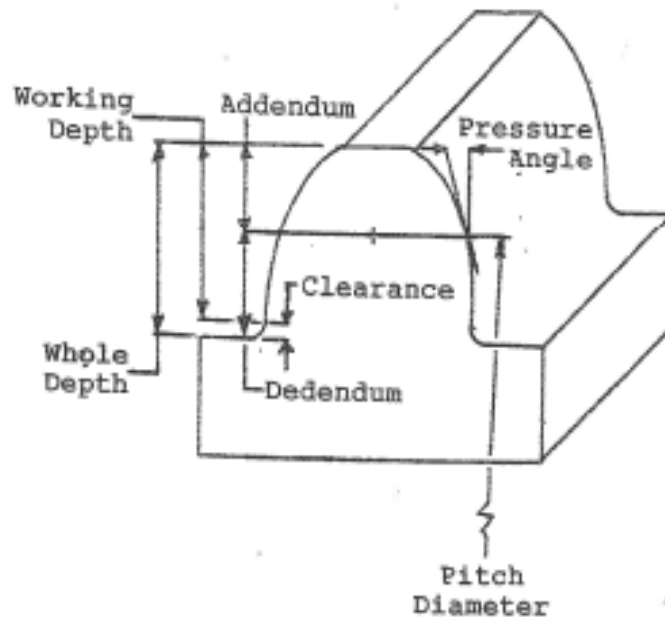
Terms

The following terms are associated with gears:

- Pinion is the smaller of two gears in mesh. The larger is called the gear regardless of which one is doing the driving.
- Ratio is the number of teeth on the gear divided by the number of teeth on the pinion.
- Pitch diameter is a basic diameter of the gear and pinion which when divided by each other equals the ratio.
- Diametral pitch is a measure of tooth size and equals the number of teeth on a gear divided by the pitch diameter. Diametral pitches usually range from 25 to 1.
- Module is a measure of tooth size in the metric system. It equals the pitch diameter in millimeters divided by the number of teeth. Modules usually range from 1 to 25. Module equals 25.400 divided by the diametral pitch.
- Pitch circle is the circumference of the pitch diameter.
- Circular pitch is the distance along the pitch circle from a point on one gear tooth to the same point on an adjacent tooth.
- Addendum of a tooth is its radial height above the pitch circle. The addendum of a standard proportion tooth equals 1.000 divided by the diametral pitch. The addendum of a pinion and mating gear are equal except in the long addendum design where the pinion addendum is increased while the gear addendum is reduced by the same amount.
- Dedendum of a tooth is its radial height below the pitch circle. The dedendum of a tooth equals 1.250 divided by the diametral pitch. The dedendum for a pinion and mating gear are equal except in the long addendum design where the pinion dedendum is decreased while the gear dedendum is increased by the same amount.

- Whole depth or total depth of a tooth equals the addendum plus the dedendum. The whole depth equals 2.250 divided by the diametral pitch.
- Working depth of a tooth equals the whole depth minus the height of the radius at the base of the tooth. The working depth equals 2.000 divided by the diametral pitch.
- Clearance equals the whole depth minus the working depth or .250 divided by the diametral pitch. The clearance is equal to the height of the radius at the base of the tooth.
- Pressure angle is the slope of the gear tooth at the pitch circle. See Figure 2.

Figure 2
Gear Tooth Terminology



Dimensions for a 2" Diametral Pitch Tooth:

$$\text{Addendum} = 1.00/2 = 0.500 \text{ inches}$$

$$\text{Dedendum} = 1.25/2 = 0.625 \text{ inches}$$

$$\text{Clearance} = 0.25/2 = 0.125 \text{ inches}$$

$$\text{Whole Depth} = 2.25/2 = 1.125 \text{ inches}$$

$$\text{Working Depth} = 2.00/2 = 1.000 \text{ inches}$$

Material

Gears are made from steel, iron, bronze, and plastic. Steel is the most widely used gear material. Iron is good because of its castability and wear characteristics. Bronze is good for gears where friction is a concern. Plastic gears have good moldability properties but have limited load carrying capability.

Many different kinds of steel can be used for gears. They range from low carbon, low alloy to high carbon, high alloy. The type used depends on load, size, and cost considerations. Low carbon, low alloy steels are used when low cost is of prime importance. High carbon, high alloy steels are used when high load and small size are the major design objectives.

Steel gears can be heat treated to improve performance by increasing strength and wear properties. Some alloys are through-hardened to the Rockwell C42 level. Others are carburized and hardened to the Rockwell C60 level on the outer shell leaving the inner core softer. This hardening technique imparts good strength and wear properties to the outer layer while the inner core gives good shock absorbing characteristics.

Gear steel comes in grades 1, 2, and 3. Higher grade numbers represent higher quality steels for higher performing gears. Some of the items controlled are material composition, residual stress, and microstructure. American Gear Manufacturers Association (AGMA) standard ANSI/AGMA 2001-D04 defines the grades of steel for gears.

Manufacture

Gear cutting processes can be classified as either generating or forming. The generating method involves moving the tool over the work piece in such a way as to create the desired shape. In the forming process, the shape of the tool is imparted on the work piece.

A generating method of cutting gear teeth that is commonly used is called hobbing. A hob is a thread-like tool with a series of slots machined across it to provide cutting surfaces. It can be fed across the gear blank from a number of directions developing several teeth at the same time. Forming methods of gear cutting include shaping and milling. Shaping uses a gear-like tool that is reciprocated up and down to impart its tooth form on the gear blank. Milling rotates a shaped tool to remove material between the gear teeth.

After cutting, some gears are heat treated to increase strength and wearability. This process causes a small amount of distortion. To restore good tooth accuracy and surface finish, heat treating is followed by a finishing operation. For gears that are heat treated to a hardness below Rockwell C42, a finishing operation called shaving is used. Shaving is similar to shaping except the tool teeth are grooved to provide additional cutting edges to remove a small amount of material. For gears that are heat treated to a hardness of Rockwell C42 and higher, grinding is used as the finishing operation. Grinding can either be a generating or forming method of finishing gears. The generating method passes an abrasive wheel over the gear in a prescribed manner to true up the teeth and produce a fine surface finish. The forming method feeds a shaped wheel between the gear teeth similar to milling.

Gear teeth are normally manufactured with pressure angles ranging from 14.5° to 25° . As the pressure angle increases, the teeth become wider at the base and narrower at the tip. This makes the teeth stronger and able to carry more load but more apt to chip at the tip if not properly designed. Pinions can be made with fewer teeth with higher pressure angles because of there being less danger of undercutting. Undercutting is an undesirable narrowing of the base of the teeth when being manufactured. Lower pressure angle teeth have a narrower base and

carry less load than higher pressure angle teeth, but the teeth are wider at the tip and less apt to chip. Finally, lower pressure angle teeth run more smoothly and quieter than higher pressure angle teeth because of having higher contact ratios. Contact ratio is a measure of the number of teeth in engagement at the same time during gear operation.

Spur Gear Design

As an exercise in gear selection, a step-by-step procedure will be demonstrated on how to design a gearset (pinion and gear) for a gearbox that is to be mass produced for a general industrial application. The gearset shall transmit 100 horsepower at a pinion speed of 1000 revolutions per minute. It shall have a ratio of 8 to 1 and shall use standard proportion 25° pressure angle teeth.

Initially, a determination must be made regarding the number of teeth in the pinion. The objective is to keep the number of teeth as low as possible to minimize cost and weight while still fulfilling all the design objectives. From The American Gear Manufacturers Association standard AGMA 908-B89, the fewest number of standard proportion 25° pressure angle teeth that a pinion can have is 14. Fewer than 14 will cause undercutting. Undercutting, as previously mentioned, is a narrowing or weakening of the base of gear teeth. It is a flaw that is caused by trying to machine a gear with too few teeth.

Thru-hardened Rockwell C42 steel and case-hardened Rockwell C60 steel will be investigated for the gearset. As a general rule of thumb for steels in this hardness range, the number of teeth in the pinion should be from 30 for low ratio (1/1) gearsets to 14 for high ratio (10/1) gearsets. As a result, a pinion with 17 teeth will be selected for the above 8 to 1 ratio gearset.

An 8 to 1 ratio gearset requires the gear to have $8 \times 17 = 136$ teeth. A ratio of 136 to 17 is not a "hunting ratio". Hunting ratios occur when each pinion tooth contacts every gear tooth before it contacts any gear tooth a second time. Hunting ratios tend to equalize tooth wear and improve tooth spacing. The test for a hunting ratio is that the number of teeth in the pinion and, separately, the number of teeth in the gear, cannot be divided by the same number, excluding 1. Both tooth numbers in a 136/17 ratio can be divided by 17. In order to make the ratio a hunting ratio, a tooth will be eliminated from the gear and a hunting ratio of 135/17 will be used. The new ratio of 7.9 to 1 is close enough to 8 to 1 for this application.

Spur Gear Rating

There are a number of methods of rating spur gears. AGMA offers two ways to rate gears. Both are contained in standard ANSI/AGMA 2001-D04. One way calculates the allowable transmitted horsepower on the pitting resistance of gear teeth contact surfaces, while the other calculates transmitted horsepower on gear teeth bending strength.

The two power rating equations will be used to evaluate the subject gearset with two different materials and four different diametral pitches (tooth sizes) in order to optimize the design. The first material will be steel, thru-hardened to Rockwell C42, while the second will be steel, case-hardened to Rockwell C60. All metallurgical properties of the pinion and gear will be assumed to be of grade 1 specification. Pinion and gear as finished surface topography are assumed to be commensurate with good manufacturing practices. The diametral pitches to be investigated shall be 7.000, 6.773, 6.350, and 6.000. The 7.000 and 6.000 diametral pitches are standard English sizes while the 6.773 (3.75 module) and 6.350 (4 module) are standard metric sizes. The two materials and the diametral pitches were selected based on preliminary analyses using the AGMA equations. The pitting resistance power rating equation transposed down to one line without the rating factors follows. In actual practice, the rating factors must be used as significant changes can result in some cases.

$$P_{ac} = (\pi n_p F I / 396,000) (d_{sac} / C_p)^2$$

P_{ac} is the pitting resistance allowable transmitted horsepower for 10 million cycles of operation at 99% reliability.

π is a constant and equals 3.142

n_p is the pinion speed which equals 1000 rpm.

F is the face width of the gears. As a general rule of thumb for industrial grade gears, $F = 1 \times d$, where d is the pinion pitch diameter which is calculated below.

I is the tooth geometry factor for pitting resistance which from AGMA 908-B89 equals .132 for 25° pressure angle standard proportion teeth and a ratio of 135/7.

d is the pinion pitch diameter, and for the four diametral pitches being investigated equals $17/7.000=2.429"$, $17/6.773=2.510"$, $17/6.350=2.677"$, and $17/6.000=2.833"$.

s_{ac} is the allowable contact stress and from ANSI/AGMA 2001-D04 equals 158,000 psi for grade 1, RC42 thru-hardened steel, and 180,000 psi for grade 1, RC60 case-hardened steel.

C_p is the elastic coefficient and from ANSI/AGMA 2001-D04 equals $2300^{.5}$ psi for a steel pinion and gear.

The equations calculating P_{ac} for the two steels and four diametral pitches are contained in Appendix I and range from 70.8 hp for thru-hardened steel and 7.000 diametral pitch to 145.9 hp for case-hardened steel and 6.000 pitch. These horsepower numbers are discussed later in this section.

The bending strength power rating equation transposed down to one line and without the rating factors follows:

$$P_{at} = (\pi n_p d F J s_{at}) / (396,000 P_d)$$

P_{at} is the bending strength allowable transmitted horsepower for 10 million cycles of operation at 99% reliability.

π is a constant and equals 3.142.

n_p is the pinion speed which 1000 rpm.

d is the pinion pitch diameter and is calculated above.

F is the face width and equals d calculated above.

J is the tooth geometry factor for bending strength which from AGMA 908-B89 equals .30.

s_{at} is the allowable bending stress and from ANSI/AGMA 2001-D04 equals 43,700 psi for grade 1, RC42 thru-hardened steel and 55,000 psi for grade 1, RC60 case-hardened steel.

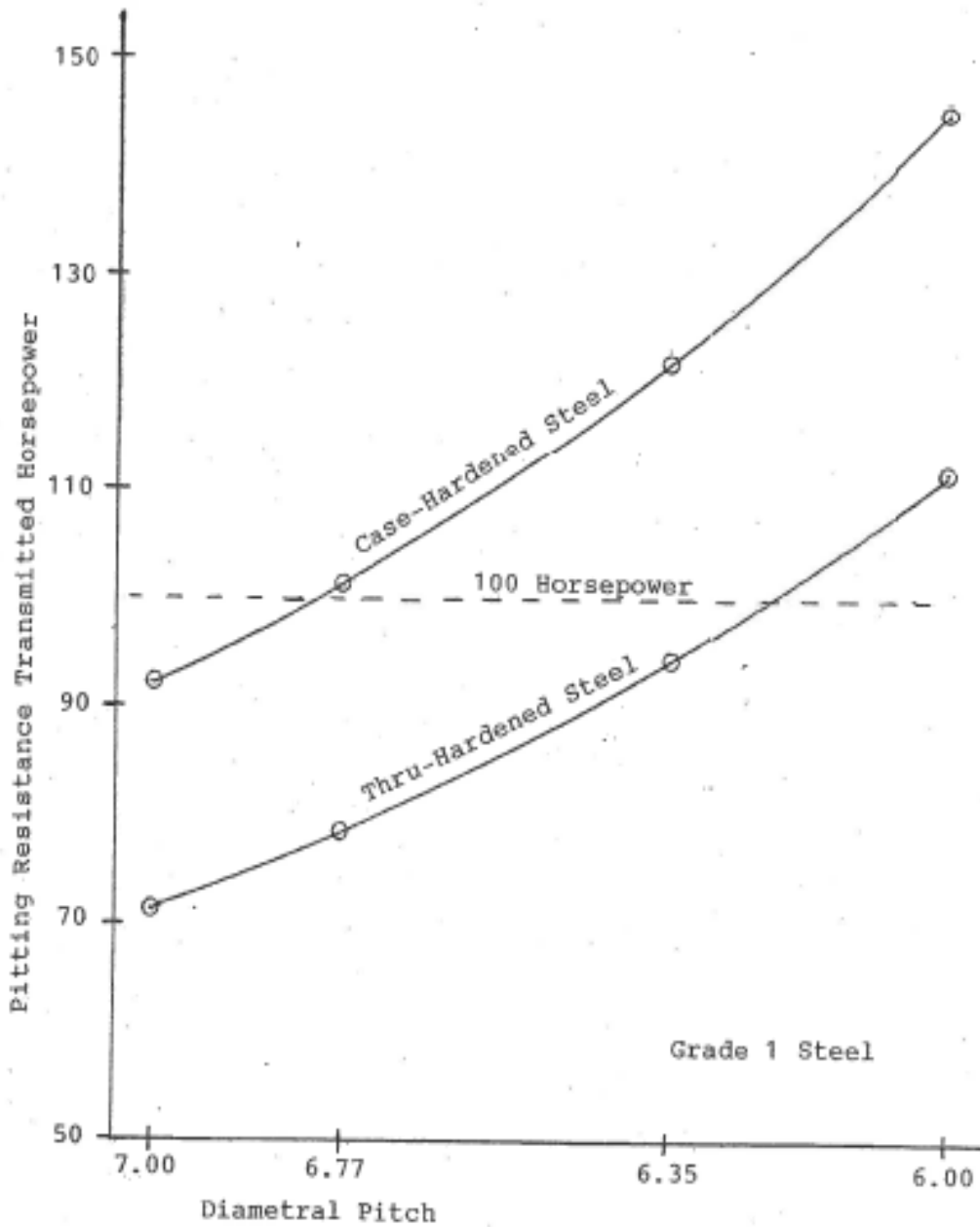
P_d is the diametral pitch which is given above.

The equations calculating P_{at} for the two steels and four diametral pitches are contained in Appendix II and range from 87.7 hp for thru-hardened steel and 7.000 diametral pitch to 175.1 hp for case-hardened steel and 6.000 pitch.

It can be seen from the results of the pitting and bending calculations that, when comparing the two, the pitting transmitted horsepowers are somewhat lower than the bending transmitted horsepowers. Since this reveals that the gearset is more likely to fail from pitting, the more conservative pitting numbers will be used to evaluate the various design options.

Figure 3 is a plot of pitting transmitted horsepower versus diametral pitch for both thru-hardened and case-hardened steel. It can be seen that, for thru-hardened steel, only the 6.000 diametral pitch gearset meets the 100 horsepower design objective while, for the case-hardened steel, the 6.000, 6.350, and 6.773 diametral pitch gears all meet the 100 horsepower design objective. Size and weight are not as important as low cost for this general industrial application; therefore, the thru-hardened 6.000 diametral pitch option is selected as the case-hardened designs are expected to be more expensive.

Figure 3
Pitting Resistance Transmitted Horsepower
Versus
Diametral Pitch



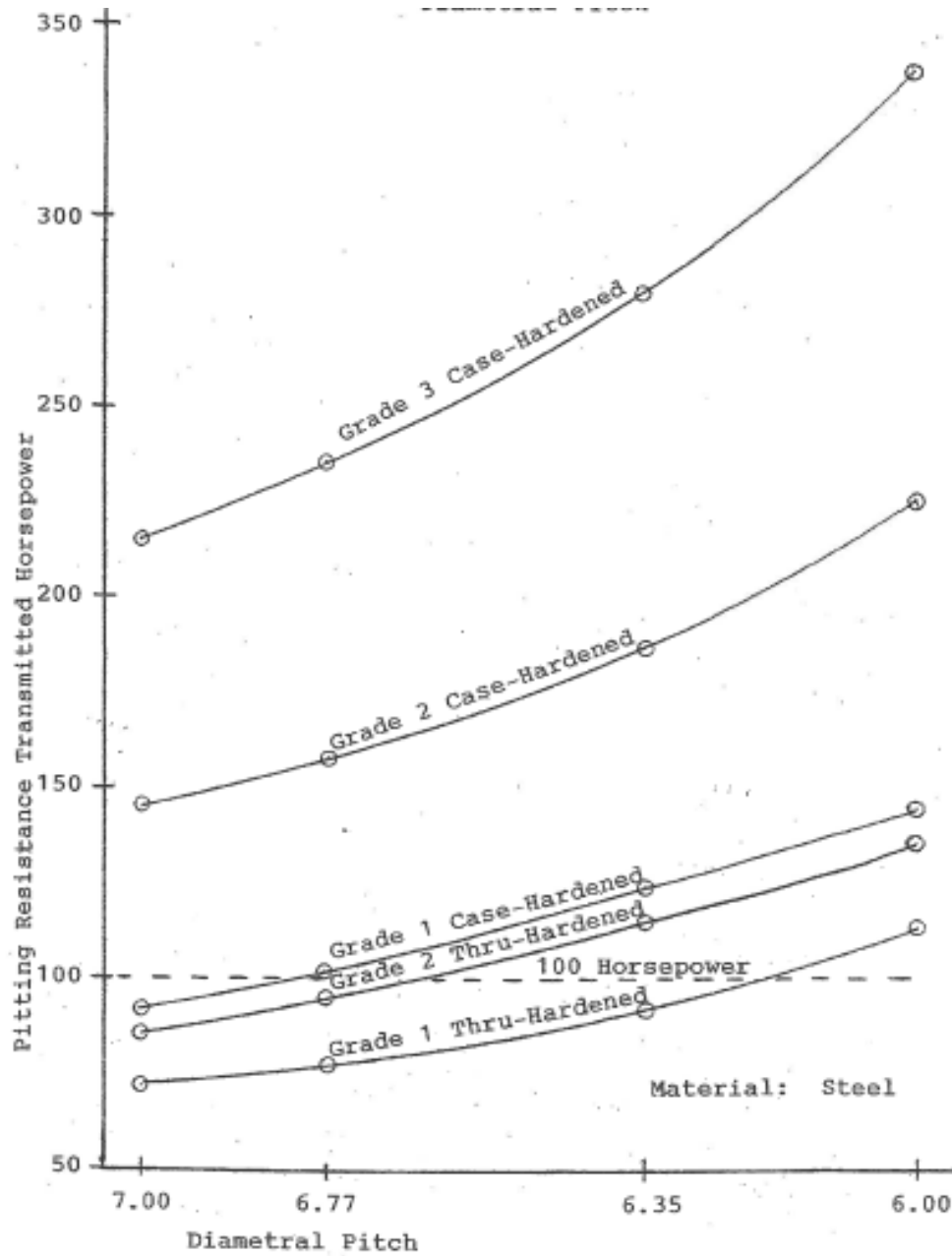
Material Upgrade

In the preceding problem, only grade 1 material was considered because of cost considerations; however, performance of the gearset can be enhanced by using higher grades of steel. Thru-hardened steel is available in grades 1 and 2 while case-hardened steel is available in grades 1, 2, and 3. As previously stated, higher grade numbers represent higher quality steel that result in improved gear performance.

In order to compare the performance of the grade 1 material previously used to the higher grades of steel, the pitting power rating equation will be repeated for the higher grade materials. The only factor that changes in the equation is the s_{ac} allowable contact stress factor. For thru-hardened steel, S_{ac} is 158,000 psi for grade 1 steel and 174,000 psi for grade 2 steel. For case-hardened steel, S_{ac} is 180,000 psi for grade 1 steel, 225,000 psi for grade 2 steel, and 275,000 psi for grade 3 steel. The calculations for the higher grade steels are in Appendix III.

The results of the new calculations with the higher grade steel along with the previous results with grade 1 steel are shown on Figure 4. It can be seen that higher grade level steel provides substantially higher horsepower ratings than grade 1 steel. Grade 2 thru-hardened steel rated 21% higher than grade 1 thru-hardened steel. Grade 2 case-hardened steel rated 56% higher than grade 1 case-hardened steel. Grade 3 case-hardened steel rated 134% higher than grade 1 case-hardened steel. This exercise demonstrates the important role that steel quality plays in the performance of gears.

Figure 4
Pitting Resistance Transmitted Horsepower
Versus
Diametral Pitch



Long Addendum Design

Normally in a gearset, the pinion is weaker than the gear. To equalize the strength of the two, a tooth modification factor called "long addendum" is used. In the long addendum design, the pinion addendum is increased while the gear addendum is reduced by the same amount. This not only increases the pinion bending strength, but it also decreases the stresses that cause pitting failure.

In the previous sample problems, standard length pinion and gear addenda were used. The pinion addendum will now be increased by 25% and the results compared. The same AGMA equations will be used. The only item that changes in the equations are the tooth geometry factors. When applying the new tooth geometry factors to the already calculated horsepower ratings, the pitting resistance horsepower is increased by 14% while the pinion tooth bending strength horsepower rating is increased by 13%. Since the long addendum tooth modification factor is easy to accommodate in manufacturing, it is a valuable engineering design tool that is available for use.

Rim Thickness

The gear rim is the ring of material that lies under the gear teeth and serves to hold and support the gear teeth. The gear rim must be of sufficient radial thickness to prevent fatigue cracks from propagating through the rim rather than through the gear teeth. ANSI/AGMA 2001-D04 recommends that gear rim thickness be no less than 1.2 times whole tooth depth. A method is presented that downgrades bending strength power ratings for gears with insufficient rim thickness.

Figure 5 has a sketch of a 3 diametral tooth gear segment. The whole depth of the teeth is 2.25 divided by 3 which equals .75 inch. The whole depth of .75 inch times 1.2 equals .90 inch which is the minimum rim thickness allowed for satisfactory gear performance.

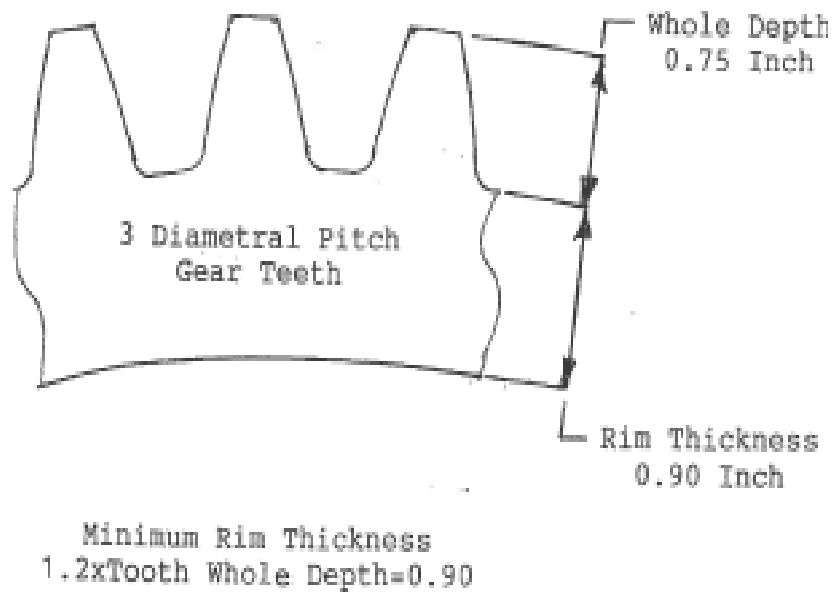
The above mentioned standard provides an equation that downgrades bending strength power ratings for gears with insufficient rim thickness as follows:

$$K_B = 1.6 \ln(2.242/m_B)$$

K_B is the rim thickness factor which is applied to bending strength power ratings to downgrade them in the event that the rim thickness to whole tooth depth ratio is less than 1.2.

m_B is the rim thickness to tooth whole depth ratio which was calculated above for Figure 5.

Figure 5 Gear Rim Thickness



Spur Gear Application

The drawing in Figure 6 is a spur gearset mounted on shafts which are supported by roller bearings. Since spur gears impose radial loads only on shafts, roller bearings, which are designed to support radial loads, are frequently used with spur gearshafts. The housing in Figure 6 has separately machined bearing seats above and below the shaft centerline. It can be seen that, in the design above the shaft centerline, the housing bearing seats must be machined during separate settings while the design below the centerline allows the housing bearing seats to be thru-bored in one setting. Thru-boring housings provide for better alignment of both gears and bearings.

Figure 7 has a section of a transmission which shows the shifter mechanism and gears. The shifter is located at the bottom and is connected to one gear of a cluster of three spur gears. The spur gear cluster slides axially on a splined shaft to mesh separately with each of the three separate spur gears located above in order to obtain three different speed ratios. The bearing mounting arrangement allows for thru-boring the housing for better gear and bearing alignment. It also fixes the right bearing and allows the left bearing to be free to move axially in order to accommodate differential thermal expansion between the shaft and housing and also to accommodate machining tolerances of the shaft and housing.

Figure 6
Spur Gears with Optional Mountings

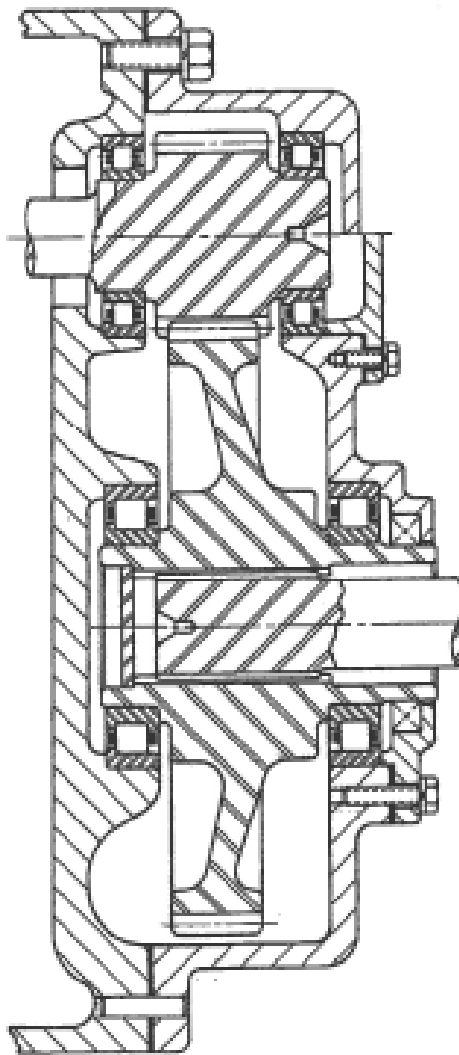
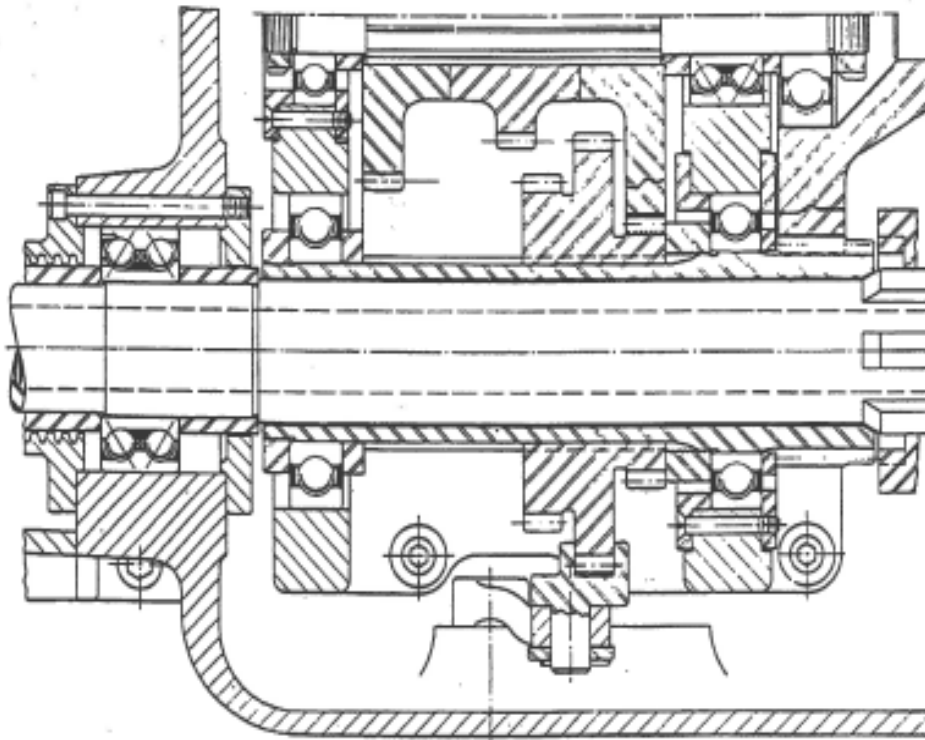


Figure 7
Multi-Speed Transmission



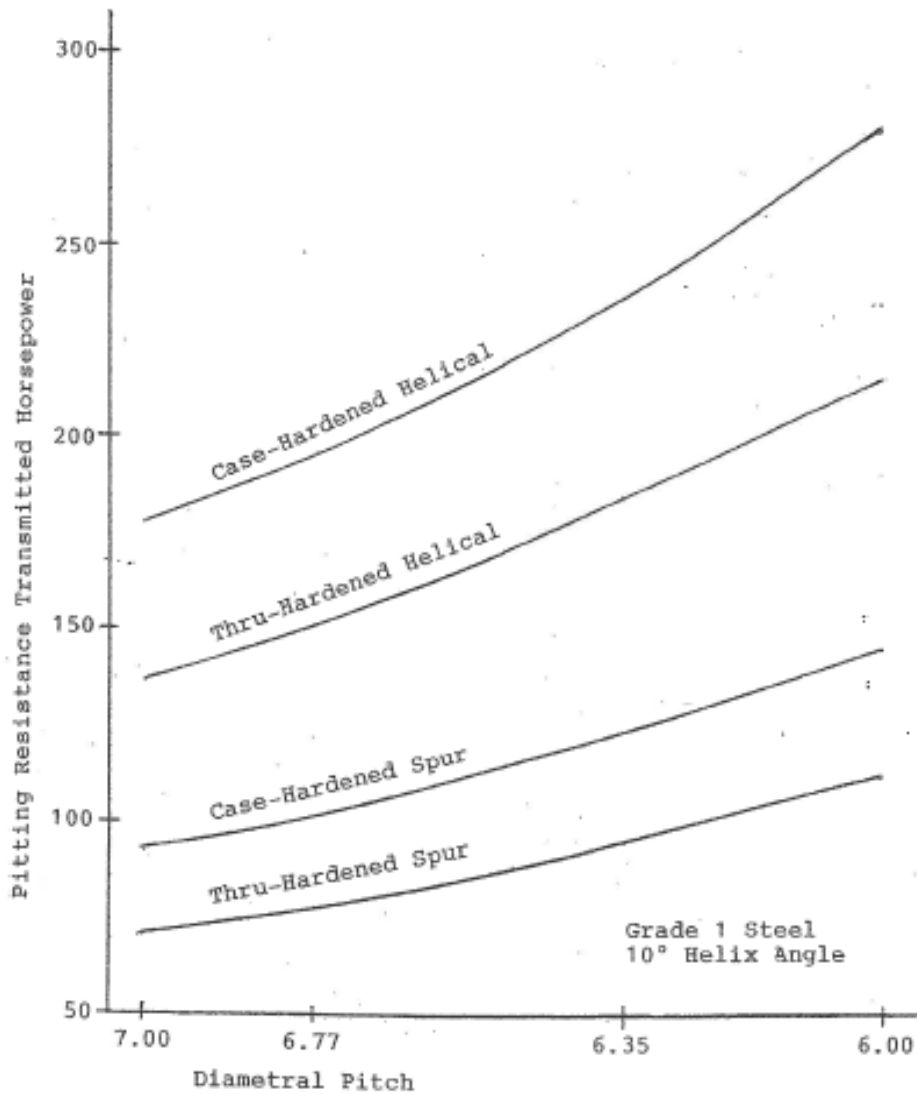
Helical/Bevel Gear Rating

The spur gearset that was previously rated will be replaced by the same size helical gearset and the power rating of the two will be compared. The helix of the new gearset will be 10° . All other aspects of the two designs will be equal. As before, grade 1 thru-hardened and grade 1 case-hardened steel with the same four diametral pitches will be evaluated. The only thing that changes in the pitting and bending equations that were previously used is the tooth geometry factor. Accordingly, the pitting tooth geometry ratio of $.255/.132$ gives helical gears a 93% increase in pitting transmitted horsepower and the bending tooth geometry factor ratio of $.56/.30$ gives the helical gears an 87% increase in bending transmitted horsepower.

Figure 8 has a plot showing the pitting transmitted horsepower ratings for spur and helical gears with the helical gear ratings being substantially higher than the spur gear ratings. Helical gears with higher helix angles can give even higher pitting and bending power ratings than the example given above.

Standard ANSI/AGMA 2003-B97 has the equations for pitting and bending horsepower ratings for bevel and spiral bevel gears. The equations are similar to those for spur and helical gears, again, except for the tooth geometry factors many of which are listed in the standard.

Figure 8
Pitting Resistance Transmitted Horsepower
Versus
Diametral Pitch



Helical/Bevel Gear Application

Figure 9 has an image of a parallel shaft double reduction helical gearbox. In a double reduction gearbox, the individual ratios are multiplied by each other to obtain the overall gearbox reduction ratio. If the overall ratio was to be achieved by a single reduction gearset, the size of the gearbox would be much larger than what is shown on Figure 9. The helical gears are straddle mounted between tapered roller bearings that support both radial and thrust loads imposed by helical gears.

Figure 10 has an image of a spiral bevel gearbox that has one input and two 90° output shafts. The ratio is one to one; therefore, it is a change of direction gearbox only. The output shaft is straddle mounted between two tapered roller bearings where the bearing located closer to the gear supports a higher portion of the load. The input shaft is overhung mounted over two tapered roller bearings. Overhung loading puts an especially heavy load on the bearing closer to the gear. Notice that the tapered roller bearings that are located closer to the gears are almost as large as the gears themselves.

Figure 11 has a sketch of the center section of an automotive drive axle. The input shaft on the right is connected to the two output shafts that deliver power to the vehicle left and right wheels. The input shaft bevel pinion gear meshes with a larger bevel ring gear which drives the center differential. The differential is composed of two sets of bevel gears that allow power to be delivered to both output shafts even when they are rotating at different speeds such as when the vehicle is rounding a corner. The input gearset is usually either spiral bevel or hypoid. The spiral bevel mesh is on a horizontal plane as shown on the sketch while the hypoid mesh is located lower. Hypoid gears are used to lower the drive shaft that is located under the center of the vehicle. Lowering the driveshaft allows automotive designers to provide more space in the passenger compartment.

Figure 9
Double Reduction Helical Gear Box

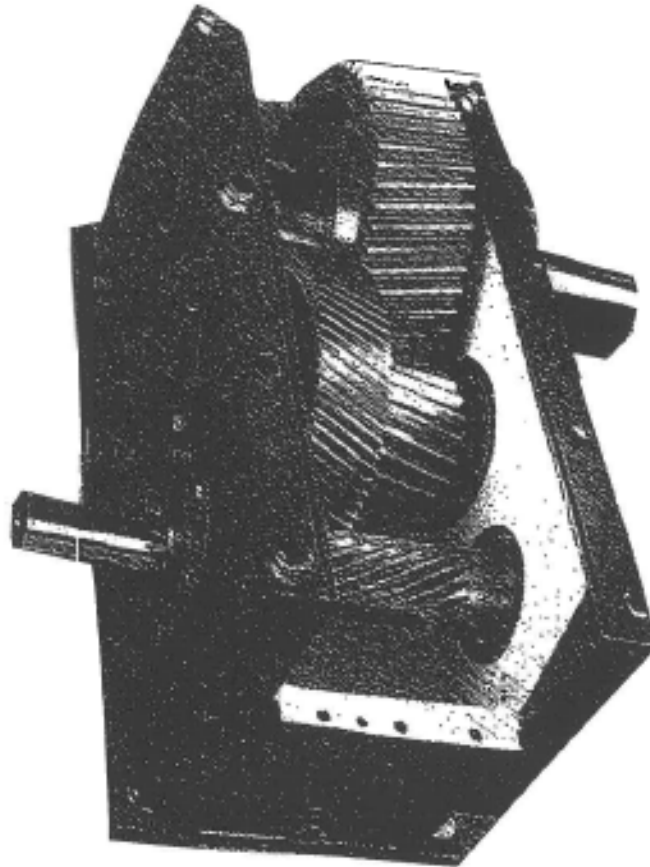


Image Courtesy of Emerson Power Transmission

Figure 10
Spiral Bevel Gearbox

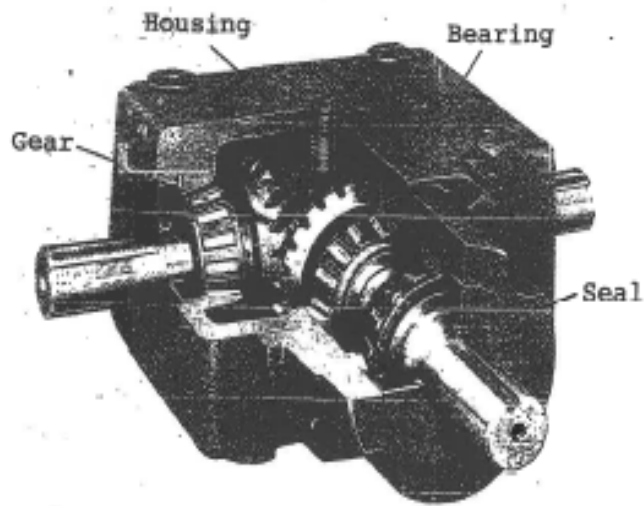
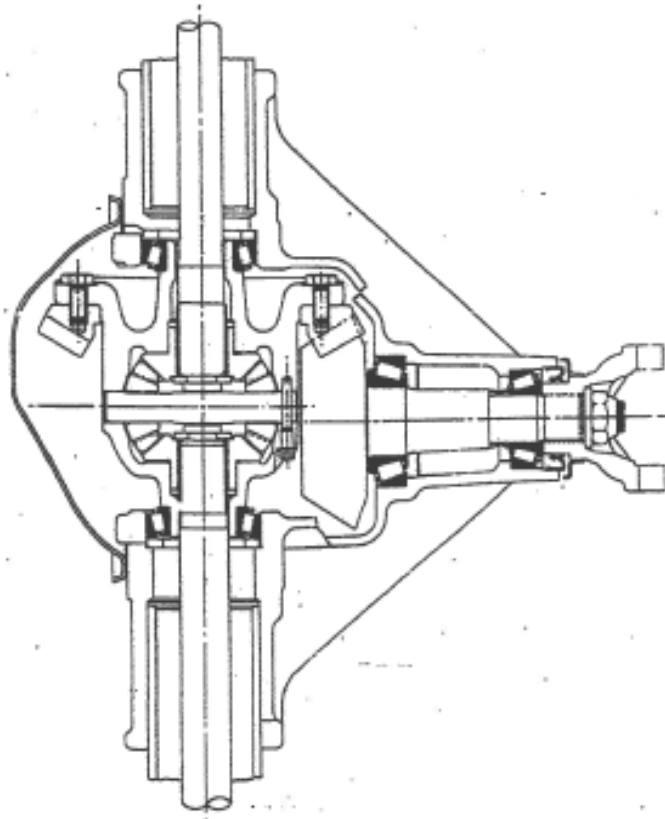


Image Courtesy of Emerson Power Transmission

Figure 11
Automotive Drive Axle Center Section



Bevel Pinion and Ring Gear
And
Bevel Gear Differential Unit

Appendix I

The pitting resistance transmitted horsepowers for the two steels and four diametral pitches are as follows:

- 1) Thru-hardened RC42 steel and 7.000 diametral pitch:
 $(3.142 \times 1000 \times 2.429 \times .132 / 396,000)(2.429 \times 158,000 / 2300)^2 = \underline{70.8 \text{ hp}}$
- 2) Case-hardened RC60 steel and 7.000 diametral pitch:
 $(3.142 \times 1000 \times 2.429 \times .132 / 396,000)(2.429 \times 180,000 / 2300)^2 = \underline{91.9 \text{ hp}}$
- 3) Thru-hardened RC42 steel and 6.773 diametral pitch:
 $(3.142 \times 1000 \times 2.510 \times .132 / 396,000)(2.510 \times 158,000 / 2300)^2 = \underline{78.2 \text{ hp}}$
- 4) Case-hardened RC60 steel and 6.773 diametral pitch:
 $(3.142 \times 1000 \times 2.510 \times .132 / 396,000)(2.510 \times 180,000 / 2300)^2 = \underline{101.4 \text{ hp}}$
- 5) Thru-hardened RC42 steel and 6.350 diametral pitch:
 $(3.142 \times 1000 \times 2.677 \times .132 / 396,000)(2.677 \times 158,000 / 2300)^2 = \underline{94.8 \text{ hp}}$
- 6) Case-hardened RC60 steel and 6.350 diametral pitch:
 $(3.142 \times 1000 \times 2.677 \times .132 / 396,000)(2.677 \times 180,000 / 2300)^2 = \underline{123.1 \text{ hp}}$
- 7) Thru-hardened RC42 steel and 6.000 diametral pitch:
 $(3.142 \times 1000 \times 2.833 \times .132 / 396,000)(2.833 \times 158,000 / 2300)^2 = \underline{112.4 \text{ hp}}$
- 8) Case-hardened RC60 steel and 6.000 diametral pitch:
 $(3.142 \times 1000 \times 2.833 \times .132 / 396,000)(2.833 \times 180,000 / 2300)^2 = \underline{145.9 \text{ hp}}$

Appendix II

The allowable bending strength transmitted horsepower for the two steels and four diametral pitches are as follows:

- 1) Thru-hardened RC42 steel and 7.000 diametral pitch:
 $(3.142 \times 1000 \times 2.429 \times 2.429 \times .30 \times 43,700) / (396,000 \times 7.000) = \underline{87.7 \text{ hp}}$
- 2) Case-hardened RC60 steel and 7.000 diametral pitch:
 $(3.142 \times 1000 \times 2.429 \times 2.429 \times .30 \times 55,000) / (396,000 \times 7.000) = \underline{110.3 \text{ hp}}$
- 3) Thru-hardened RC42 steel and 6.773 diametral pitch:
 $(3.142 \times 1000 \times 2.510 \times 2.510 \times .30 \times 43,700) / (396,000 \times 6.773) = \underline{96.8 \text{ hp}}$
- 4) Case-hardened RC60 steel and 6.773 diametral pitch:
 $(3.142 \times 1000 \times 2.510 \times 2.510 \times .30 \times 55,000) / (396,000 \times 6.773) = \underline{121.8 \text{ hp}}$
- 5) Thru-hardened RC42 steel and 6.350 diametral pitch:
 $(3.142 \times 1000 \times 2.677 \times 2.677 \times .30 \times 43,700) / (396,000 \times 6.350) = \underline{117.4 \text{ hp}}$
- 6) Case-hardened RC60 steel and 6.350 diametral pitch:
 $(3.142 \times 1000 \times 2.677 \times 2.677 \times .30 \times 55,000) / (396,000 \times 6.350) = \underline{147.7 \text{ hp}}$
- 7) Thru-hardened RC4 steel and 6.000 diametral pitch:
 $(3.142 \times 1000 \times 2.833 \times 2.833 \times .30 \times 43,700) / (396,000 \times 6.000) = \underline{139.1 \text{ hp}}$
- 8) Case-hardened RC60 steel and 6.000 diametral pitch:
 $(3.142 \times 1000 \times 2.833 \times 2.833 \times .30 \times 55,000) / (396,000 \times 6.000) = \underline{175.1 \text{ hp}}$

Appendix III

- 1) Thru-hardened grade 2 steel and 7.000 diametral pitch:
 $(3.142 \times 1000 \times 2.429 \times .132/396,000)(2.429 \times 174,000/2300)^2 = \underline{85.9 \text{ hp}}$
- 2) Case-hardened grade 2 steel and 7.000 diametral pitch:
 $(3.142 \times 1000 \times 2.429 \times .132/396,000)(2.429 \times 225,000/2300)^2 = \underline{143.6 \text{ hp}}$
- 3) Case-hardened grade 3 steel and 7.000 diametral pitch:
 $(3.142 \times 1000 \times 2.429 \times .132/396,000)(2.429 \times 275,000/2300)^2 = \underline{214.6 \text{ hp}}$
- 4) Thru-hardened grade 2 steel and 6.773 diametral pitch:
 $(3.142 \times 1000 \times 2.510 \times .132/396,000)(2.510 \times 174,000/2300)^2 = \underline{94.8 \text{ hp}}$
- 5) Case-hardened grade 2 steel and 6.773 diametral pitch:
 $(3.142 \times 1000 \times 2.510 \times .132/396,000)(2.510 \times 225,000/2300)^2 = \underline{158.5 \text{ hp}}$
- 6) Case-hardened grade 3 steel and 6.773 diametral pitch:
 $(3.142 \times 1000 \times 2.510 \times .132/396,000)(2.510 \times 275,000/2300)^2 = \underline{236.8 \text{ hp}}$
- 7) Thru-hardened grade 2 steel and 6.350 diametral pitch:
 $(3.142 \times 1000 \times 2.677 \times .132/396,000)(2.677 \times 174,000/2300)^2 = \underline{115.0 \text{ hp}}$
- 8) Case-hardened grade 2 steel and 6.350 diametral pitch:
 $(3.142 \times 1000 \times 2.677 \times .132/396,000)(2.677 \times 225,000/2300)^2 = \underline{192.3 \text{ hp}}$
- 9) Case-hardened grade 3 steel and 6.350 diametral pitch:
 $(3.142 \times 1000 \times 2.677 \times .132/396,000)(2.677 \times 275,000/2300)^2 = \underline{287.2 \text{ hp}}$
- 10) Thru-hardened grade 2 steel and 6.000 diametral pitch:
 $(3.142 \times 1000 \times 2.833 \times .132/396,000)(2.833 \times 174,000/2300)^2 = \underline{136.3 \text{ hp}}$
- 11) Case-hardened grade 3 steel and 6.000 diametral pitch:
 $(3.142 \times 1000 \times 2.833 \times .132/396,000)(2.833 \times 225,000/2300)^2 = \underline{227.9 \text{ hp}}$
- 12) Case-hardened grade 3 steel and 6.000 diametral pitch:
 $(3.142 \times 1000 \times 2.833 \times .132/396,000)(2.833 \times 275,000/2300)^2 = \underline{340.4 \text{ hp}}$