Gear Materials, Properties, and Manufacture

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GEAR MATERIALS, PROPERTIES, AND MANUFACTURE

Edited by

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Contents

Failure Analysis, Fatigue Life Prediction, and Mechanical Testing

Preface

Gears, because of their unique contribution to the operation of so many machines and mechanical devices, have received special attention from the technical community for more than two millennia. New developments in gear technology, particularly from the materials point-of-view, have also been covered in detail by ASM International for many years. Numerous forums, conference proceedings, books, and articles have been devoted to the understanding of gear performance by examining gear tribology, failure modes, the metallurgy of ferrous gear materials, heat treatment, gear manufacturing methods, and testing. All of these important technical aspects of gear technology are brought together in the present offering, *Gear Materials, Properties, and Manufacture*.

Chapter 1, "Basic Understanding of Gears," discusses the various types of gears used, important gear nomenclature, and applied stresses and strength requirements associated with gears. It also provides an overview of several important topics that are covered in greater detail in subsequent chapters, namely, gear materials, gear manufacture, and heat treatment. Gear tribology and lubrication is covered in Chapter 2. Lubrication-related failures (pitting, wear, and scuffing), elastohydrodynamic lubrication, lubricant selection, and gear lubricant application are among the subjects described.

Chapters 3 and 4 describe both metallic (ferrous and nonferrous alloys) and plastic gear materials, respectively. Emphasis in Chapter 3 has been placed on the properties of carburized steels, the material of choice for high-performance power transmission gearing. The increasing use of plastics for both motion-carrying and power transmission applications is covered in Chapter 4.

Chapters 5, 6, and 7 address methods for manufacturing gears including metal removal processes (machining, grinding, and finishing), casting, forming, and forging (including recent advances in near-net shape forging of gears), and powder metallurgy processing. Injection molding, another important method for the manufacture of plastic gears, is covered in Chapter 4.

The heat treatment of gears is reviewed in Chapters 8 through 12. Both through hardening and surface hardening methods are reviewed. Again, emphasis has been placed on carburizing, the most common heat treatment applied to gear steels. It should be noted that some of the material presented in these chapters was adapted, with the kind permission of the author, from *Heat Treatment of Gears: A Practical Guide for Engineers*, by A.K. Rakhit (ASM International, 2000). Dr. Rakhit's book is an excellent resource for those seeking a more in-depth reference guide to gear heat treatment.

Failure analysis, fatigue life prediction, and mechanical testing are examined in Chapters 13, 14, and 15, respectively. In Chapter 13, "Gear Failure Modes and Analysis," emphasis has been placed on two of the most common types of gear failure—bending fatigue and contact fatigue. Bending fatigue of carburized steels is also discussed in depth in Chapter 3.

In summary, this book is intended for gear metallurgists and materials specialists, manufacturing engineers, lubrication technologists, and analysts concerned with gear failures who seek a better understanding of gear performance and gear life. It supplements other gear texts that emphasize the design, geometry, and theory of gears.

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CHAPTER 1

Basic Understanding of Gears

GEARS are machine elements that transmit rotary motion and power by the successive engagements of teeth on their periphery. They constitute an economical method for such transmission, particularly if power levels or accuracy requirements are high. Gears have been in use for more than three thousand years and they are an important element in all manner of machinery used in current times. Application areas for gears are diverse and include—to name a few:

- Small, low-cost gears for toys
- Gears for office equipment
- Bicycle gears
- Appliance gears
- Machine tool gears
- Control gears
- Automotive gears
- Transportation gears
- Marine gears
- Aerospace gears
- Gears in the oil and gas industry
- Gears for large mills that make cement, grind iron ore, make rubber, or roll steel

Gears range in size from recently developed micrometer-sized gears for electric motors no bigger than a grain of sand to gears as large as 30 m (100 ft) in diameter. Gear materials range from lightweight plastics to ultrahigh-strength heat-treated steels.

Gear Nomenclature

Before discussing the various types of gears used, this section will review some of the terms used in the gear industry to describe the design of gears and gear geometries. Figure 1 shows schematically typical gear nomenclature. It

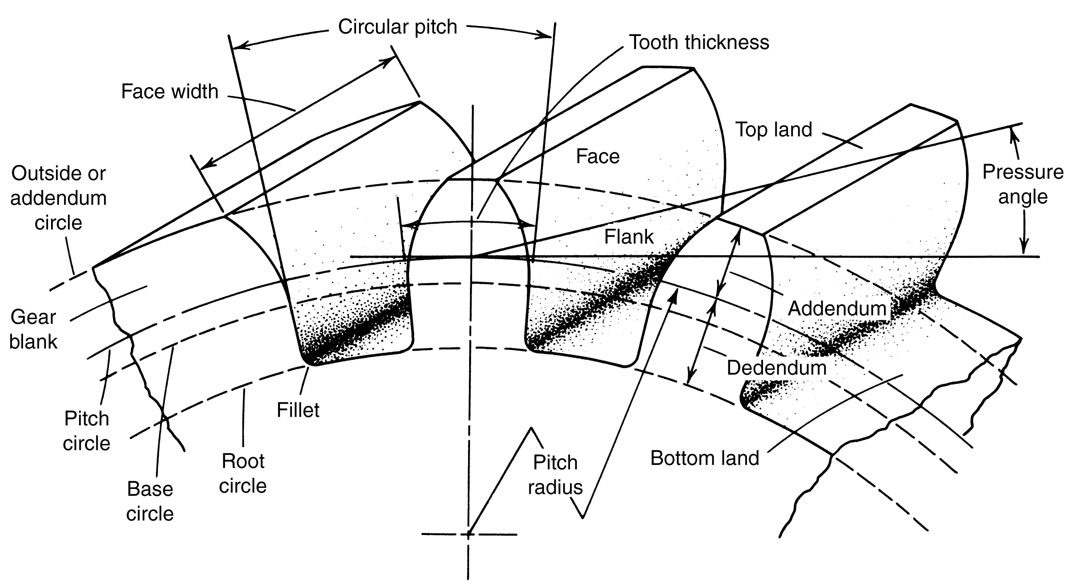

Fig. 1 Schematic of typical gear tooth nomenclature

should be noted that only the most common terms are discussed below. More detailed information on gear nomenclature can be found in various standards published by the American Gear Manufacturers Association (AGMA), most notably AGMA 1012-F90, "Gear Nomenclature, Definitions of Terms with Symbols."

active profile. The part of the gear tooth profile that actually comes in contact with the profile of the mating gear while in mesh (Fig. 2).

addendum. The height of the tooth above the pitch circle (Fig. 1).

backlash. The amount by which the width of a tooth space exceeds the thickness of the engaging tooth on the operating pitch circle (Fig. 3).

base circle. The circle from which the involute tooth profiles are generated (Fig. 1).

bottom land. The surface at the bottom of a tooth space adjoining the fillet (Fig. 1 and 2).

center distance. The distance between the axes of rotation between two mating gears.

circular pitch. Length of arc of the pitch circle between corresponding points on adjacent teeth (Fig. 1).

circular thickness. The length of arc between the two sides of a gear tooth at the pitch circle.

dedendum. The depth of the tooth below the pitch circle (Fig. 1).

diametral pitch (DP). A measure of tooth size in the English system. In units, it is the number of teeth per inch of pitch diameter. As the tooth size increases, the diametral pitch decreases (Fig. 4). Diametral pitches range from 0.5 to 200. Coarse pitch gears are those with a diametral pitch of ≤20. Fine pitch gears are those with a diametral pitch of >20. Table 1 shows the various tooth dimensions for different diametral pitches of spur gears.

face width. The length of the gear teeth in an axial plane (Fig. 1).

fillet radius. The radius of the fillet curve at the base of the gear tooth (Fig. 2).

gear. A geometric shape that has teeth uniformly spaced around the circumference. In general, a gear is made to mesh its teeth with another gear.

gear blank. The workpiece used for the manufacture of a gear, prior to machining the gear teeth.

gear pinion. When two gears mesh together, the smaller of the two is called the pinion; the larger is called the gear (Fig. 5).

gear quality numbers. AGMA gear quality numbers ranging from 3 to 15 identify the

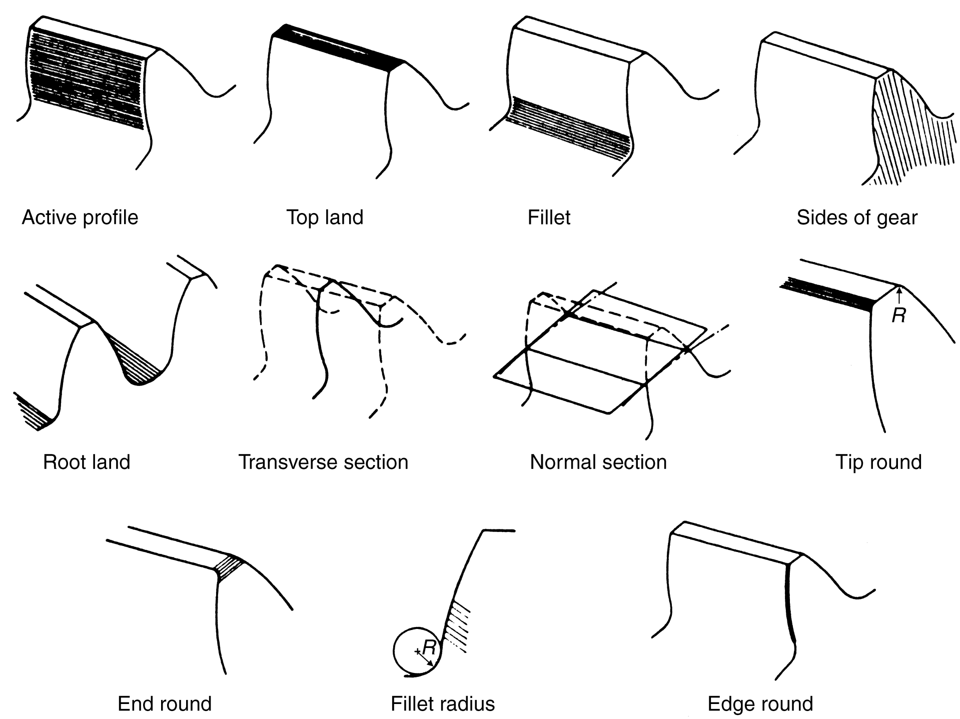

Fig. 2 Nomenclature of gear contact areas and boundary zones

accuracy level of the tooth element tolerances permissible in the manufacture of a particular gear in terms of its specialized use. The higher the number, the greater the level of accuracy. Numbers 3 through 7 are for commercial applications such as appliances, numbers 8 through 13 are for precision applications, and numbers 14 and 15 are for ultraprecision applications. The permissible tolerances for the different quality numbers may be obtained from the AGMA standards, which show the type of gear and the permissible tolerances and inspection dimensions.

gear ratio. The ratio of the larger to the smaller number of teeth in a pair of gears.

helix angle. The angle between any helix and an element of its cylinder. In helical gears and worms, it is at the standard pitch circle unless otherwise specified.

involute gear tooth. A gear tooth whose profile is established by an involute curve outward from the base circle (Fig. 6).

normal section. A section through a gear that is perpendicular to the tooth at the pitch circle (Fig. 2).

pitch circle. The circumference of a gear measured at the point of contact with the mating gear (Fig. 1 and 7).

pitch diameter. The diameter of the pitch circle.

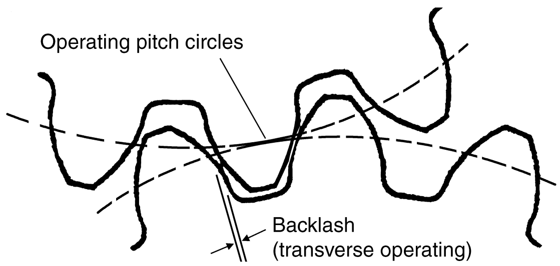

Fig. 3 Schematic of gear backlash. Source: Ref 1

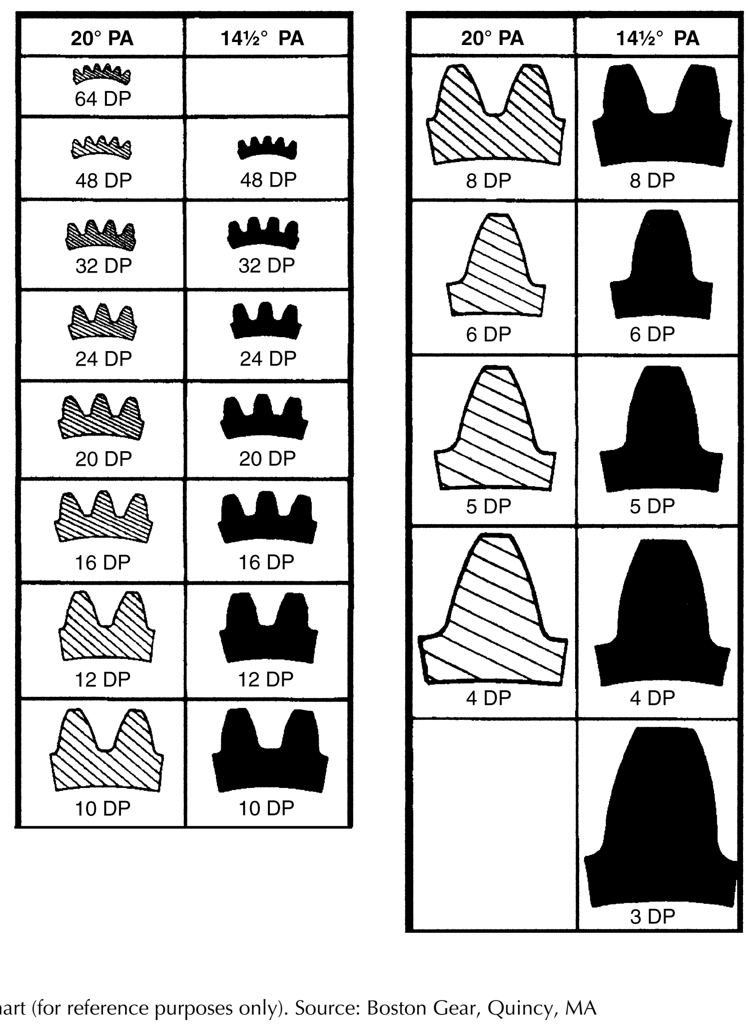

Fig. 4 Tooth gage chart (for reference purposes only). Source: Boston Gear, Quincy, MA

pitch line. In a cross section of a rack, the pitch line corresponds to the pitch circle in the cross section of the gear (Fig. 7).

pitch point. The tangency point of the pitch circles of two mating gears (Fig. 7).

pitch radius. The radius of the pitch circle in a cross section of gear teeth in any plane other than a plane of rotation (Fig. 1).

pressure angle. The angle between a tooth profile and a radial line at its pitch point (Fig. 1). The pressure angle of an involute gear tooth is determined by the size ratio between the base circle and the pitch circle (Fig. 8). Common pressure angles used by the gear industry are 14.5, 20, and 25°.

rack. A rack is a gear having a pitch circle of infinite radius. Its teeth lie along a straight line on a plane. The teeth may be at right angles to the edge of the rack and mesh with a spur gear (Fig. 5 and 9b), or the teeth on the rack may be at some other angle and engage a helical gear (Fig. 10b).

Table 1 Gear cutting table showing various tooth dimensions for different diametral pitches of spur gears

Diametral pitch	Circular pitch, in.	Thickness of tooth on pitch line, in.	Depth to be cut in gear(a), in.	Addendum, in.
3	1.0472	0.5236	0.7190	0.3333
4	0.7854	0.3927	0.5393	0.2500
5	0.6283	0.3142	0.4314	0.2000
6	0.5236	0.2618	0.3565	0.1667
8	0.3927	0.1963	0.2696	0.1250
10	0.3142	0.1571	0.2157	0.1000
12	0.2618	0.1309	0.1798	0.0833
16	0.1963	0.0982	0.1348	0.0625
20	0.1571	0.0785	0.1120	0.0500
24	0.1309	0.0654	0.0937	0.0417
32	0.0982	0.0491	0.0708	0.0312
48	0.0654	0.0327	0.0478	0.0208
64	0.0491	0.0245	0.0364	0.0156

(a) Hobbed gears. Source: Boston Gear, Quincy, MA

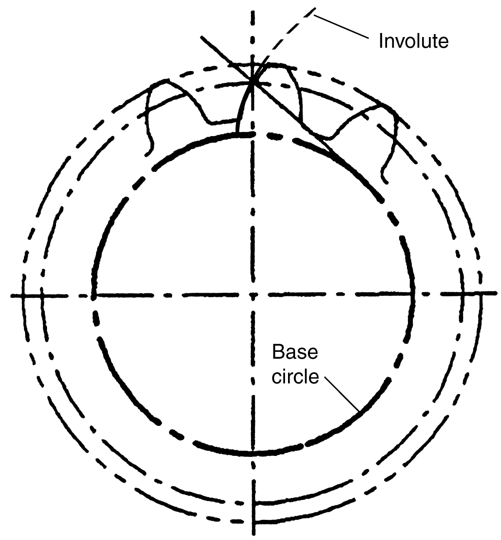

Fig. 6 Schematic of an involute gear tooth. Source: Ref 1

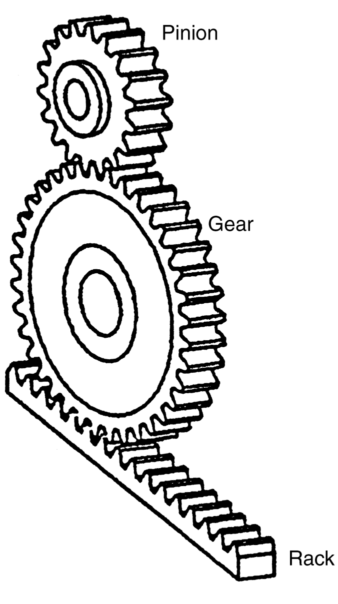

Fig. 5 The pinion, gear, and rack portions of a spur gear. Source: Ref 1

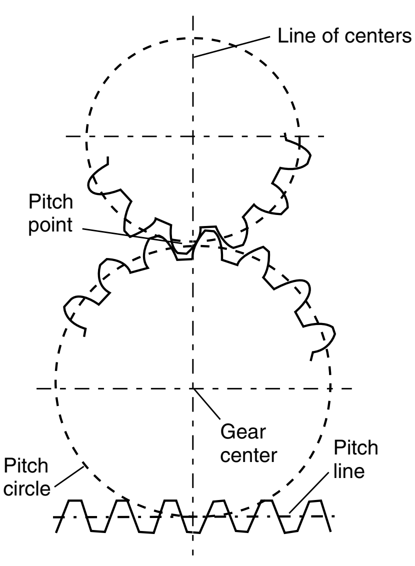

Fig. 7 Schematic of pitch nomenclature. Source: Ref 1

root circle. The root circle coincides with the bottoms of the tooth spaces (Fig. 1).

tooth thickness. The thickness of the tooth measured at the pitch circle (Fig. 1).

top land. The surface of the top of a tooth (Fig. 1 and 2).

transverse section. A section through a gear perpendicular to the axis of the gear (Fig. 2).

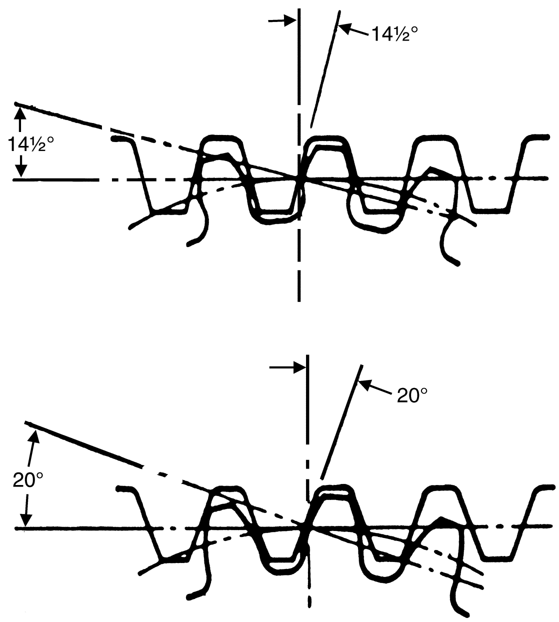

Fig. 8 Schematic of two common pressure angles. Source: Boston Gear, Quincy MA

Types of Gears

There is a wide variety of types of gears in existence, each serving a range of functions. In order to understand gearing, it is desirable to classify the more important types in some way. One approach is by the relationship of the shaft axes on which the gears are mounted. As listed in Table 2, shafts may be parallel, intersecting, or nonintersecting and nonparallel.

Types of Gears that Operate on Parallel Shafts

Spur gears (Fig. 5 and 9) are used to transmit motion between parallel shafts or between a shaft and a rack. The teeth of a spur gear are radial, uniformly spaced around the outer periphery, and parallel to the shaft on which the gear is mounted. Contact between the mating teeth of a spur gear is in a straight line parallel to the rotational axes, lying in a plane tangent to the pitch cylinders of the gears (a pitch cylinder is the imaginary cylinder in a gear that rolls without slipping on a pitch cylinder or pitch plane of another gear).

Helical gears (Fig. 10a) are used to transmit motion between parallel or crossed shafts or between a shaft and a rack by meshing teeth that lie along a helix at an angle to the axis of the shaft. Because of this angle, mating of the teeth occurs such that two or more teeth of each gear are always in contact. This condition permits smoother action than that of spur gears. How-

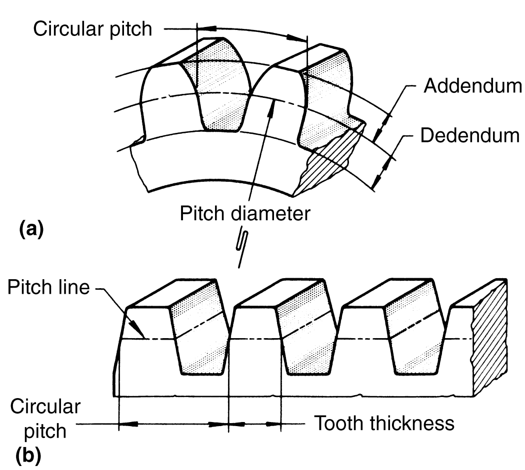

Fig. 9 Sections of a spur gear (a) and a spur rack (b)

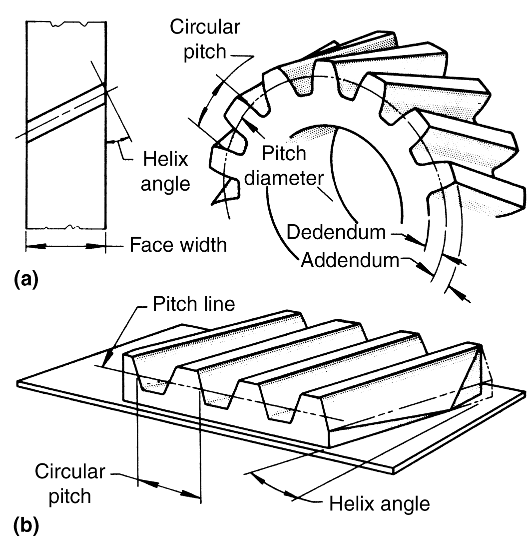

Fig. 10 Sections of a helical gear (a) and a helical rack (b)

ever, unlike spur gears, helical gears generate axial thrust, which causes slight loss of power and requires thrust bearings.

Herringbone gears (Fig. 11), sometimes called double helical gears, are used to transmit motion between parallel shafts. In herringbone gears, tooth engagement is progressive, and two or more teeth share the load at all times. Because they have right-hand and left-hand helixes, herringbone gears are usually not subject to end thrust. Herringbone gears can be operated at higher pitch-line velocities than spur gears.

Internal gears are used to transmit motion between parallel shafts. Their tooth forms are similar to those of spur and helical gears except that the teeth point inward toward the center of the gear. Common applications for internal gears include rear drives for heavy vehicles, planetary gears, and speed-reducing devices. Internal gears are sometimes used in compact designs because the center distance between the internal gear and its mating pinion is much smaller than that required for two external gears. A typical relation between an internal gear and a mating pinion is shown in Fig. 12.

Table 2 Types of gears in common use

Parallel axes
Spur external
Spur internal
Helical external
Helical internal
Intersecting axes
Straight bevel
Zerol bevel
Spiral bevel
Face gear
Nonintersecting and nonparallel axes
Crossed helical
Single-enveloping worm
Double-enveloping worm
Hypoid
Spiroid

Types of Gears that Operate on Intersecting Shafts

Bevel gears transmit rotary motion between two nonparallel shafts. These shafts are usually at 90° to each other.

Straight bevel gears (Fig. 13a) have straight teeth that, if extended inward, would intersect at the axis of the gear. Thus, the action between mating teeth resembles that of two cones rolling on each other (see Fig. 14 for angles and terminology). The use of straight bevel gears is generally limited to drives that operate at low speeds and where noise is not important.

Spiral bevel gears (Fig. 13b) have teeth that are curved and oblique. The inclination of the teeth results in gradual engagement and continuous line contact or overlapping action; that is, more than one tooth will be in contact at all times. Because of this continuous engagement, the load is transmitted more smoothly from the driving to the driven gear than with straight bevel gears. Spiral bevel gears also have greater load-carrying capacity than their straight counterparts. Spiral bevel gears are usually preferred to straight bevel gears when speeds are greater than 300 m/min (1000 sfm), and particularly for very small gears.

Zerol bevel gears (Fig. 13c) are curved-tooth bevel gears with zero spiral angle. They differ from spiral bevel gears in that the teeth

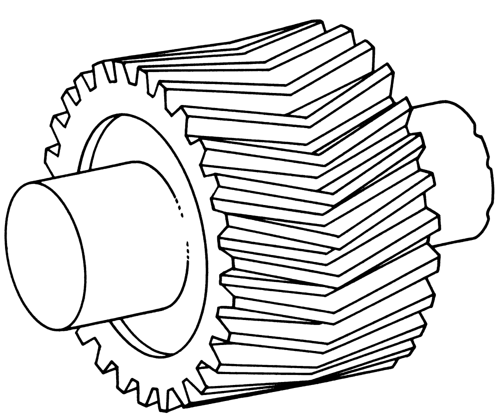

Fig. 11 A typical one-piece herringbone gear. The opposed helixes permit multiple-tooth engagement and eliminate end thrust.

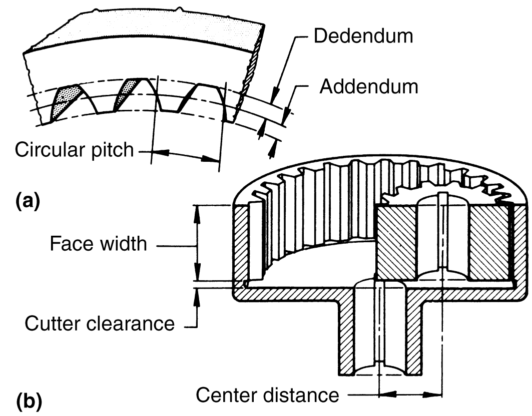

Fig. 12 Section of a spur-type internal gear (a) and relation of internal gear with mating pinion (b)

are not oblique. They are used in the same way as spiral bevel gears, and they have somewhat greater tooth strength than straight bevel gears.

Face gears have teeth cut on the end face of a gear, as the term face gear implies. They are not ordinarily thought of as bevel gears, but functionally they are more akin to bevel gears than to any other type.

A spur pinion and a face gear are mounted (like bevel gears) on shafts that intersect and have a shaft angle (usually 90°). The pinion bearings carry mostly radial load, while the gear bearings have both thrust and radial load. The mounting distance of the pinion from the pitch-cone apex is not critical, as it is in bevel or hypoid gears. Figure 15 shows the terminology used with face gears.

The pinion that goes with a face gear is usually made spur, but it can be made helical if necessary. The formulas for determining the dimensions of a pinion to run with a face gear are no different from those for the dimensions of a pinion to run with a mating gear on parallel axes. The pressure angles and pitches used are similar to spur gear (or helical gear) practice.

The gear must be finished with a shaper-cutter that is almost the same size as the pinion. Equipment for grinding face gears is not available. The teeth can be lapped, and they can be shaved without too much difficulty, although ordinarily shaving is not used.

The face gear tooth changes shape from one end of the tooth to the other. The face width of the gear is limited at the outside end by the radius at which the tooth becomes pointed. At the inside end, the limit is the radius at which

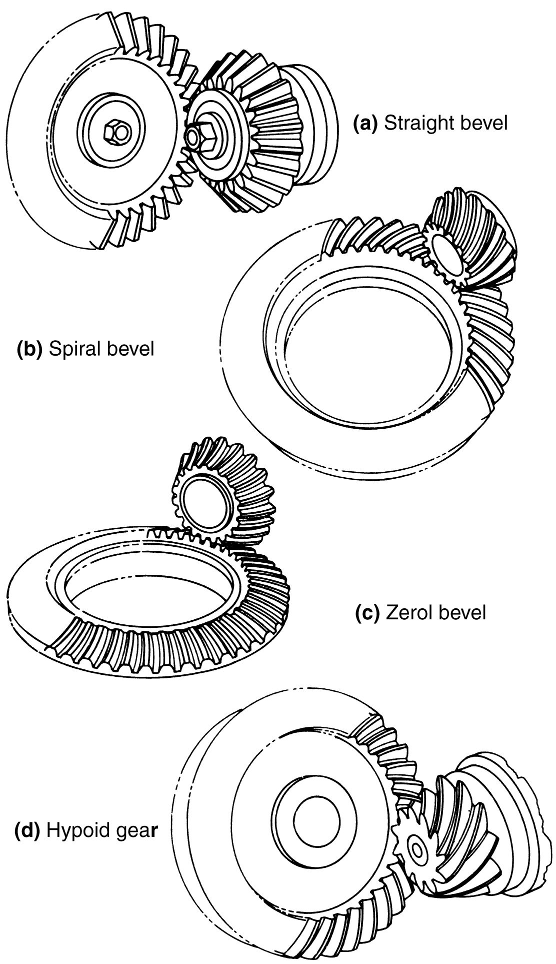

Fig. 13 Three types of bevel gears and a hypoid gear

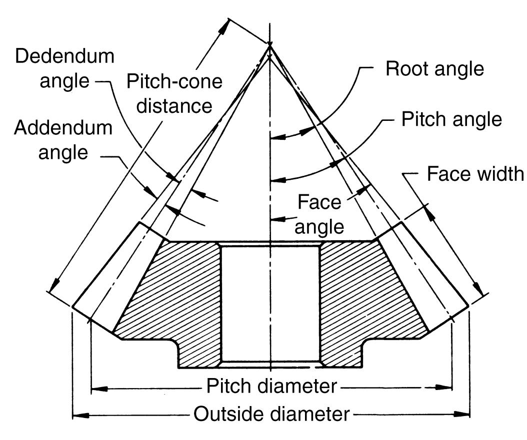

Fig. 14 Angles and terminology for straight bevel gears

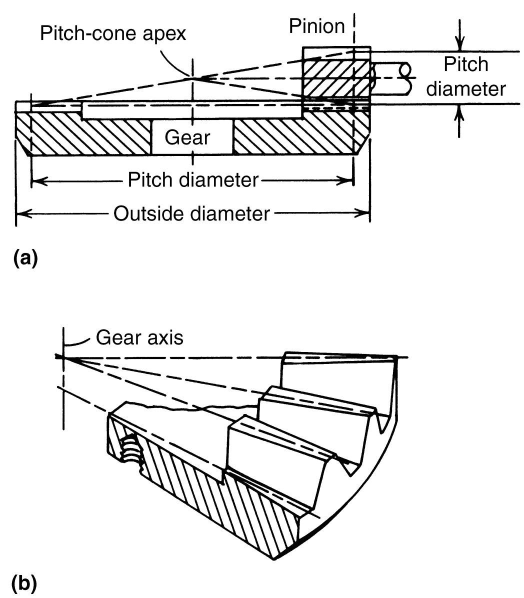

Fig. 15 Face gear terminology. (a) Cross-sectional view showing gear and pinion positions. (b) Relationship of gear teeth to gear axis

undercut becomes excessive. Due to practical considerations, it is usually desirable to make the face width somewhat short of these limits. The pinion to go with a face gear is usually made with a 20° pressure angle.

Types of Gears that Operate on Nonparallel and Nonintersecting Shafts

Worm gear sets are usually right-angle drives consisting of a worm gear (or worm wheel) and a worm. A single-enveloping worm gear set has a cylindrical worm, but the gear is throated (that is, the gear blank has a smaller diameter in the center than at the ends of the cylinder, the concave shape increasing the area of contact between them) so that it tends to wrap around the worm. In the double-enveloping worm gear set, both members are throated, and both members wrap around each other. A double-enveloping worm gear set is shown in Fig. 16. Worm gear sets are used where the ratio of the speed of the driving member to the speed of the driven member is large, and for a compact right-angle drive.

Crossed-helical gears are essentially nonenveloping worm gears, that is, both members are cylindrical (Fig. 17). The action between mating teeth has a wedging effect, which results in sliding on tooth flanks. These gears have low load-carrying capacity, but are useful where shafts must rotate at an angle to each other.

Hypoid gears (Fig. 13d) are similar to spiral bevel gears in general appearance. The important difference is that the pinion axis of the hypoid pair of gears is offset somewhat from the gear axis. This feature provides many design advantages. In operation, hypoid gears run even more smoothly and quietly than spiral bevel gears and are somewhat stronger.

Spiroid gears consist of a tapered pinion that somewhat resembles a worm (Fig. 18) and a gear member that is a face gear with teeth curved in a lengthwise direction; the inclination to the tooth is like a helix angle, but not a true helical spiral. The combination of a high gear ratio in compact arrangements, low cost when mass produced, and good load-carrying capacity makes these gears attractive in many applications.

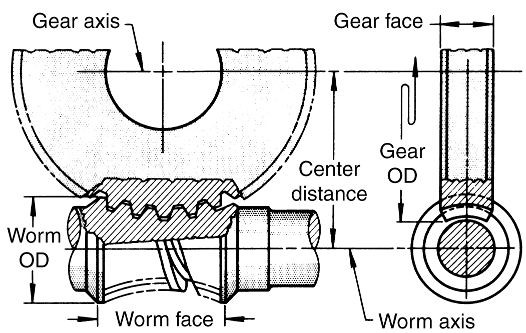

Fig. 16 Mating of worm gear (worm wheel) and worm in a double-enveloping worm gear set

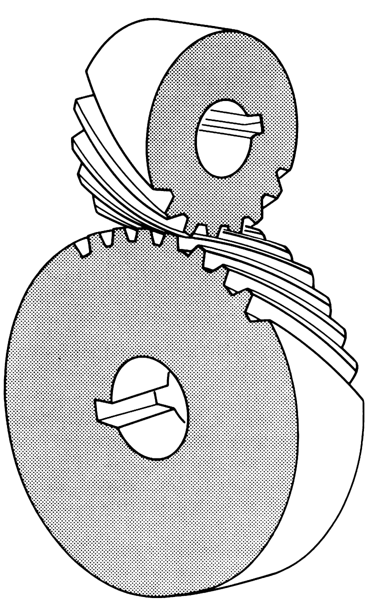

Fig. 17 Mating crossed-axes helical gears

Proper Gear Selection

The first step in designing a set of gears is to select the correct type. In many cases, the geometric arrangement of the apparatus that needs a gear drive will considerably affect the selec-

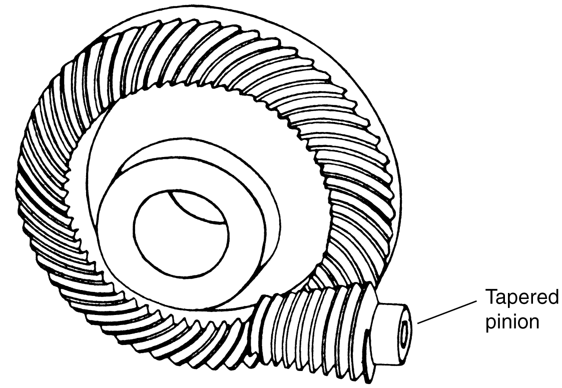

Fig. 18 Spiroid gear design

tion. If the gears must be on parallel axes, then spur or helical gears are appropriate. Bevel and worm gears can be used if the axes are at right angles, but they are not feasible with parallel axes. If the axes are nonintersecting and non-parallel, then crossed-helical gears, hypoid gears, worm gears, or Spiroid gears can be used. Worm gears, though, are seldom used if the axes are not at right angles to each other.

There are no dogmatic rules that tell the designer which gear to use. The choice is often made after weighing the advantages and disadvantages of two or three types of gears. Some generalizations, though, can be made about gear selection.

External helical gears are generally used when both high speeds and high horsepowers are involved. External helical gears have been built to carry as much as 45,000 kW (60,000 hp) of power on a single pinion and gear. Larger helical gears could also be designed and built. It is doubtful if any other type of gear could be built and used successfully to carry this much power on a single mesh.

Bevel and Hypoid Gears. Bevel gears are ordinarily used on right-angle drives when high efficiency is needed. These gears can usually be designed to operate with 98% or better efficiency. Hypoid gears do not have as good efficiency as bevel gears, but hypoid gears can carry more power in the same space, provided the speeds are not too high.

Worm gears are ordinarily used on right-angle drives when very high ratios (single-thread worm and gear) are needed. They are also widely used in low-to-medium ratios (multiple-thread worm and gear) as packaged speed reducers. Single-thread worms and worm gears are used to provide the mechanical indexing accuracy on many machine tools. The critical function of indexing hobbing machines and gear shapers is nearly always done by worm gear drive. Worm gears seldom operate at efficiencies above 90%.

Spur gears are relatively simple in design and in the machinery used to manufacture and check them. Most designers prefer to use them wherever design requirements permit.

Spur gears are ordinarily thought of as slow-speed gears, while helical gears are thought of as high-speed gears. If noise is not a serious design problem, spur gears can be used at almost any speed that can be handled by other types of gears. Aircraft gas-turbine precision spur gears sometimes operate at pitch-line speeds above 50 m/s (10,000 sfm). In general, though, spur gears are not used much above 20 m/s (4000 sfm).

Basic Applied Stresses (Ref 2)

The loads applied to one tooth by the action of its mating tooth are at any moment of time a line contact at the most; or, at the least, a point contact (more detailed information on gear tooth contact can be found in Chapter 14, "Fatigue and Life Prediction"). As the loads are increased, the line may lengthen or even broaden, or the point may expand to a rounded area.

The basic stresses applied to a gear tooth include the six types listed in Fig. 19; often, a combination of two or three types are applied at a time. Commonly they are tensile, compressive, shear (slide), rolling, rolling-slide, and torsion. Each type of gear tooth will have its own characteristic stress patterns.

Spur Gear. As the contacting tooth moves up the profile of the loaded tooth, a sliding-rolling action takes place at the profile interface. At the pitchline, the stresses are pure rolling. Above the pitchline, the rolling-sliding action again takes over, but the sliding will be in the opposite direction. Keep in mind that the action on the profile of the contacting tooth is exactly the same as the loaded tooth except in reverse

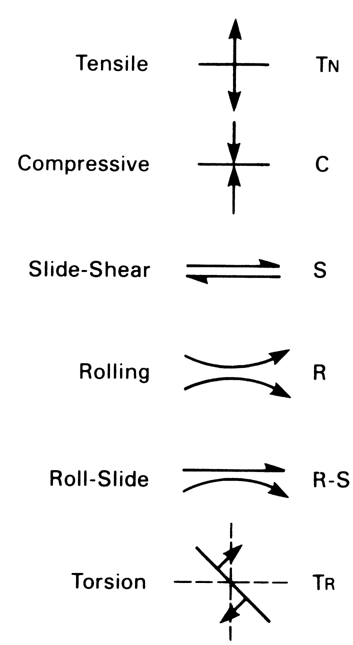

Fig. 19 Basic stresses that are applied to gear teeth. Often, two or three are simultaneously applied to a specific area. Source: Ref 2

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order (see Fig. 20). The sliding action of two surfaces, when lubricated properly, will have no problem. However, surface disparities, insufficient lubrication, improper surface hardness, higher temperatures, and abrasive or adhesive foreign particles will contribute to a breakdown during a sliding contact. At the same time, there is a tensile stress at the root radius of the loaded side of the tooth and a compressive stress at the root radius of the opposite side.

Helical Gear. The helical gear tooth receives the same contact action as the spur gear; i.e., a rolling-sliding action from the lowest point of active profile up to the pitchline, rolling over the pitchline, then sliding-rolling from the pitchline over the addendum. An additional stress is being applied to the helical tooth; a lateral sliding action is applied at all contact levels, including the pitchline. The force component at 90° to the direction of rotation increases as the helical angle increases. Resultants of this side thrust are often overlooked (see Fig. 21). The web between the center shaft hub and the outer gear rim is constantly undergoing a cycle of bending stress; it is not uncommon for a relatively thin web to fail in bending fatigue. If the hub of the gear faces against a thrust bearing, the bearing itself is under a constant thrust load. The shaft carrying the gear undergoes a continual rotation bending stress. It is also not uncommon to have such a shaft fail by rotational bending fatigue. The above secondary stresses are found only in a gear of a single-helix pattern. A double-helical gear or a herringbone gear will not have a side thrust component of stress; therefore, the entire stress load will be absorbed by the teeth.

One additional stress that should be discussed at this time is a stress common to all gearing because it involves rolling surfaces. It is a shear stress running parallel to the surface at a distance from 0.18 to 0.3 mm (0.007 to 0.012 in.) below the surface. The distance below the surface given above is the average depth for a normal loading condition. The actual depth of maximum shear could be deeper, depending on the radius of curvature of the mating surfaces and the tangential forces being applied. In one instance there has been evidence of rolling loads above the shear strength as deep as 0.86 mm (0.034 in.). The subsurface shear stress is most often the originator of initial line pitting along the pitchline of gear teeth, line pitting low on the profile due to tooth tip interference, line pitting along the tooth tip due to the same tooth tip interference, and subsurface rolling contact fatigue. The subject of rolling contact fatigue is discussed more fully in Chapters 3, "Ferrous and Nonferrous Alloys" and 13, "Gear Failure Modes and Analysis."

Straight Bevel Gear. The straight bevel gear undergoes the same stresses as discussed above, including a very slight helical action laterally. The larger sliding action component is parallel to the axis of the gears and tends to push

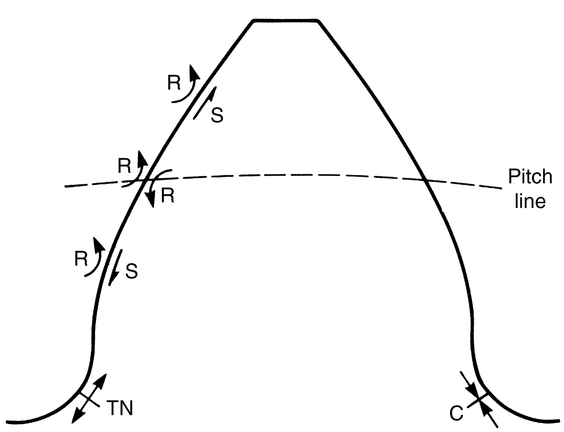

Fig. 20 Diagramatic stress areas on basic spur gear tooth. Source: Ref 2

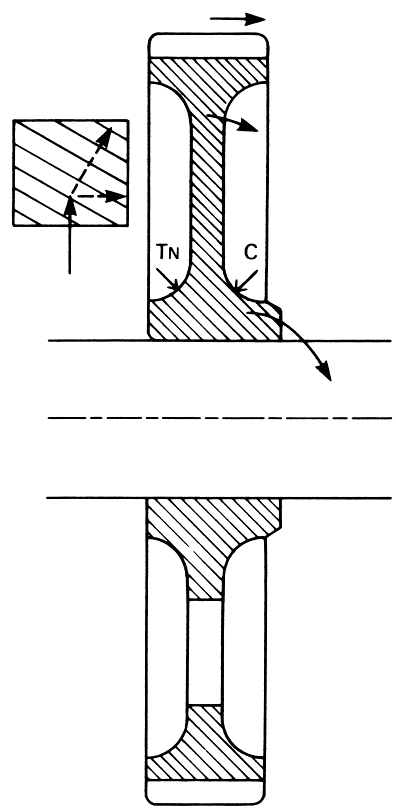

Fig. 21 Secondary stresses set up in associated parameters of a helical gear due to the side thrust action of the helix. Source: Ref 2

the gears apart, causing a higher profile contact, and to exert a rotational bending stress in the web of the part as well as in the shaft.

Spiral Bevel Gear. Aside from all the stresses applied above, a spiral bevel gear has a resultant peculiar to itself. As the rolling-sliding stress tends to move in a straight line laterally, the progression of the points along the stress line moves in a bias across the profile of the tooth. As long as at least two teeth are in contact, the resulting load per unit area is well within reasonable limits. However, there are circumstances (and it may be only momentary) when there is a 1-to-1 tooth contact. This very narrow line contact may be accepting an extremely high load per unit area, and a line of pitting will result early in the life of the tooth. Careful attention should be given to the design characteristics of these parts, such as spiral angle and pressure angle.

Hypoid Gear. The hypoid gearing has the same applied stresses as those discussed for the spiral bevel, but sliding becomes the more predominant factor. This predominance increases as the axis of the pinion is placed farther from the central axis of the gear, and is maximum when the set becomes a high-ratio hypoid.

Strength (Ref 2)

The strength of any component is measured by the amount of stress that can be tolerated before permanent strain (deformation) takes place.

Strain, or deflection under load, is a constant for steel regardless of hardness or heat treatment. The amount of deflection under load of a thin gear web or the shank of a pinion cannot be changed by heat treatment or by use of a stronger material. Hooke's law is the same: A change of deflection can be accomplished only by a change of design.

Bending strength of a gear tooth is the amount of load per unit area acceptable at the root radius to the point of permanent deformation. Permanent deformation of a carburized tooth is usually accompanied by a crack at the root radius, whereas with a noncarburized tooth, actual bending may occur. The root radius is mentioned as the point of deformation because it is the area of greatest stress concentration in tension. Also, stress (load per unit area) calculations assume that the load is applied at the pitchline or the midheight of the tooth. Actually, the realistic stress at the root radius varies from approximately one-half, when the load is applied low on the active profile, to double, when the load is applied near the tooth tip. Bending strength of the root radius is a function of the surface hardness and the physical condition of the surface, such as smoothness, sharpness of radius, and/or corrosive pitting.

The strength of the core material—i.e., the basic material under the carburized steel case—is generally to be considered as compressive strength rather than tensile strength. It measures the ability to withstand surface pressures that may crush through the case and/or brinell (indent) the surface.

Torsional strength of a pinion shank or of a shaft is a bit more complex. The maximum tensile stress is at the surface in a direction 45° from the central axis or longitudinal direction. The maximum shear stress, also at the surface, is longitudinal (parallel to the central axis) and transverse (90° across the central axis) (see Fig. 22). The strength at the surface is a function of surface hardness; therefore, surface-originated torsional tensile failures of carburized parts are rare unless a specific type of stress raiser is present at the surface. This is not so with through hardened or non-heat treated parts since the strength is uniform throughout the part. Under this condition, torsional tensile failure is expected to originate at the surface. In most instances of torsional failure of carburized or induction hardened shafts and pinion shanks, the initial fracture is along the

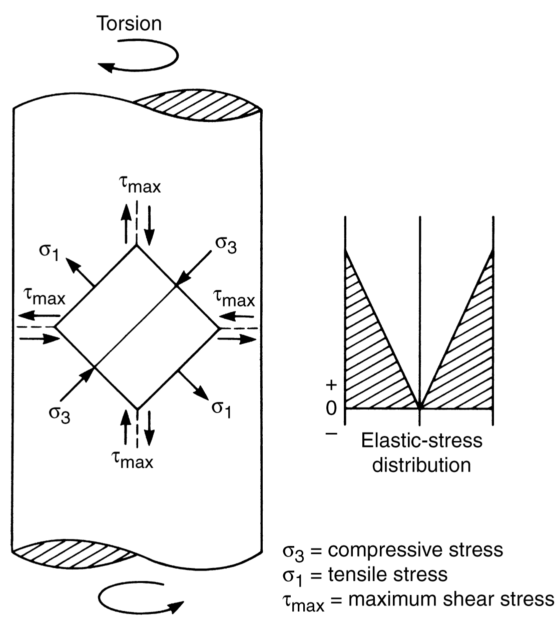

Fig. 22 Free-body diagram of maximum tensile and shear stress orientation on a surface element of a shaft in a torsional mode. Both maximums are at the surface. Stress is considered to be zero at the central axis. Source: Ref 2

shear plane (i.e., longitudinal or transverse), and not at the 45° angle. This means that the shear strength of the subsurface material is the controlling factor. Shear strength is considered to be only about 60% of the tensile strength. The area most vulnerable to the origin of torsional shear failure of a shaft is the transition zone between the case and the core of either a carburized or an induction hardened part. The maximum applied stress often exceeds the shear strength of the material at this area and initiates a start of subsurface failure.

Gear Materials

A variety of cast irons, powder-metallurgy materials, nonferrous alloys, and plastics are used in gears, but steels, because of their high strength-to-weight ratio and relatively low cost, are the most widely used gear materials for heavy duty, power transmission applications. Consequently, steel gears receive primary consideration in this chapter.

Among the through-hardening steels in wide use are 1040, 1060, 4140, and 4340. These steels can also be effectively case hardened by induction heating. Among the carburizing steels used in gears are 1018, 1524, 4026, 4118, 4320, 4620, 4820, 8620, and 9310 (AMS 6260). Table 3 lists specific application areas for commonly used gear steels. Many high-performance gears are carburized. Some special-purpose steel gears are case hardened by either carbonitriding or nitriding. Other special-purpose gears, such as those used in chemical or food-processing equipment, are made of stainless steels or nickel-base alloys because of their corrosion resistance, their ability to satisfy sanitary standards, or both. Gears intended for operation at elevated temperatures may be made of tool steels or elevated-temperature alloys.

Most gears are made of carbon and low-alloy steels, including carburizing steels and the limited number of low-alloy steels that respond favorably to nitriding. In general, the steels selected for gear applications must satisfy two basic sets of requirements that are not always compatible—those involving fabrication and processing and those involving service. Fabrication and processing requirements include machinability, forgeability, and response to heat treatment as it affects fabrication and processing. Service requirements are related to the ability of the gear to perform satisfactorily under the conditions of loading for which it was designed and thus encompass all mechanical-property requirements, including fatigue strength and response to heat treatment (see the section "Selection Guidelines" presented below).

Table 3 Recommended steels for various applications and gear types

Typical industrial application	Gear design type	Typical material choice
Differentials		
Automotive	Hypoid, spiral/straight bevel	4118, 4140, 4027, 4028, 4620, 8620, 8622, 8626
Heavy truck	Hypoid, spiral/straight bevel	4817, 4820, 8625, 8822
Drives		
Industrial	Helical, spur rack and pinion, worm	1045, 1050, 4140, 4142, 4150, 4320, 4340, 4620
Tractor-accessory	Crossed-axis helical, helical	1045, 1144, 4118, 4140
Engines		
Heavy truck	Crossed-axis helical, spur, worm	1020, 1117, 4140, 4145, 5140, 8620
Equipment		
Earth moving	Spiral/straight bevel, zerol	1045, 4140, 4150, 4340, 4620, 4820, 8620, 9310
Farming	Face, internal, spiral/straight bevel, spur	4118, 4320, 4817, 4820, 8620, 8822
Mining, paper/steel mill	Helical, herringbone, miter, spur, spur rack and pinion	1020, 1045, 4140, 4150, 4320, 4340, 4620, 9310
Starters		
Automotive	Spur	1045, 1050
Transmissions		
Automotive	Helical, spur	4027, 4028, 4118, 8620
Heavy Truck	Helical, spur	4027, 4028, 4620, 4817, 5120, 8620, 8622, 9310
Marine	Helical, helical conical, spiral bevel	8620, 8622
Off highway	Helical, internal, spiral/straight bevel, spur	1118, 5130, 5140, 5150, 8620, 8822, 9310
Tractor	Herringbone, internal, spur	4118, 4140, 8822

Source: Ref 3

Because resistance to fatigue failure is partly dependent upon the cleanness of the steel and upon the nature of allowable inclusions, melting practice may also be a factor in steel selection and may warrant selection of a steel produced by vacuum melting or electroslag refining. The mill form from which a steel gear is machined is another factor that may affect its performance. Many heavy-duty steel gears are machined from forged blanks that have been processed to provide favorable grain flow consistent with load pattern rather than being machined from blanks cut from mill-rolled bar.

Selection Guidelines. In all gears the choice of material must be made only after careful consideration of the performance demanded by the end-use application and total manufactured cost, taking into consideration such issues as machining economics. Key design considerations require an analysis of the type of applied load, whether gradual or instantaneous, and the desired mechanical properties, such as bending fatigue strength or wear resistance, all of which define core strength and heat treating requirements.

Different areas in the gear tooth profile see different service demands. Consideration must be given to the forces that will act on the gear teeth, with tooth bending and contact stress, resistance to scoring and wear, and fatigue issues being paramount. For example, in the root area, good surface hardness and high residual compressive stress are desired to improve endurance, or bending fatigue life. At the pitch diameter, a combination of high hardness and adequate subsurface strength are necessary to handle contact stress and wear and to prevent spalling.

Numerous factors influence fatigue strength, including:

- Hardness distribution, as a function of case hardness, case depth, core hardness
- Microstructure, as a function of retained austenite percentage, grain size, carbides (size, type, distribution), nonmartensitic phases
- Defect control, as a function of residual compressive stress, surface finish, geometry, intergranular toughness

More detailed information on the factors that influence the properties of gear steels can be found in Chapter 3, "Ferrous and Nonferrous Alloys."

Gear Manufacturing Methods

Gears can be made by a variety of manufacturing processes. This section will briefly review these processes. For the manufacture of metal gears, the reader should consult Chapters 5, "Machining, Grinding, and Finishing," 6, "Casting, Forming and Forging," and 7, "Powder Metallurgy." Methods for making plastic gears are described in Chapter 4, "Plastics."

Metal Removal Processes

As shown in Fig. 23, gear blanks can be shaped by a number of cutting (machining) and finishing processes. Often blanks are processed

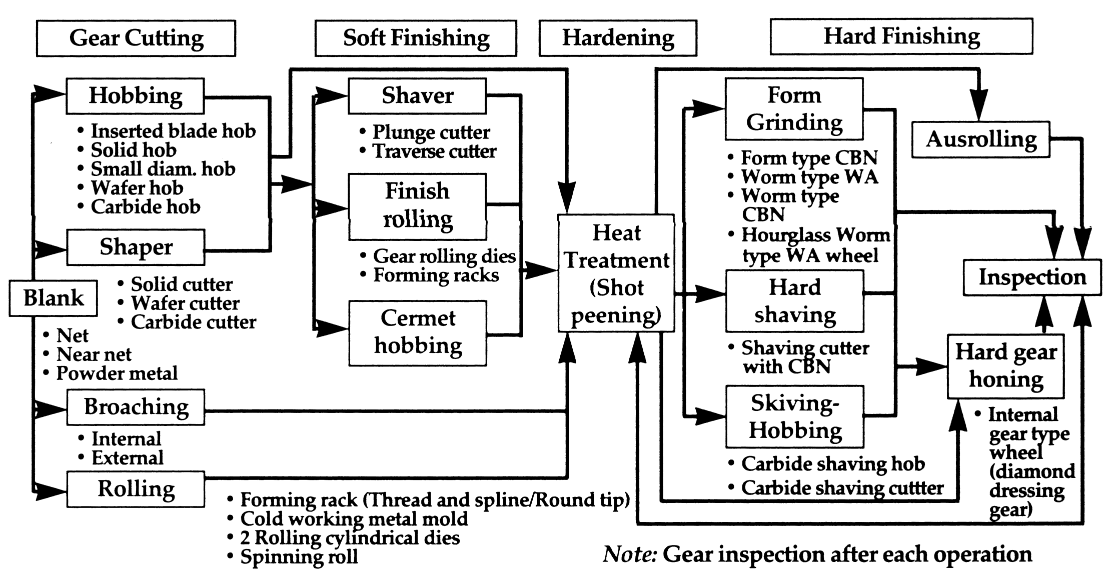

Fig. 23 Examples of various gear manufacturing processes. Source: Ref 3

by a series of rough cutting and finishing operations. Gears made by machining/finishing have the highest AGMA quality tolerance levels than gears made by competing processes (see Table 1 in Chapter 6). Machining and finishing processes make up about 60% of gear manufacturing costs (Fig. 24).

Broaching is a machining operation which rapidly forms a desired contour in a workpiece by moving a cutter, called a broach, entirely past the workpiece. The broach has a long series of cutting teeth that gradually increase in height. The broach can be made in many different shapes to produce a variety of contours. The last few teeth of the broach are designed to finish the cut rather than to remove considerably more metal. Broaches are often used to cut internal gear teeth, racks, and gear segments on small gears, and usually are designed to cut all teeth at the same time.

Grinding is a process that shapes the surface by passes with a rotating abrasive wheel. Grinding is not a practical way to remove large amounts of metal, so it is used to make very fine-pitch teeth, or to remove heat treat distortion from large gears that have been cut and then fully hardened. Many different kinds of grinding operations are used in gear manufacture.

Hobbing. This is a gear cutting method that uses a tool resembling a worm gear in appearance, having helically spaced cutting teeth. In a single-pitch hob, the rows of teeth advance exactly one pitch as the hob makes one revolution. With only one hob, it is possible to cut interchangeable gears of a given pitch of any number of teeth within the range of the hobbing machine.

Honing is a low-speed finishing process used chiefly to produce uniform high dimensional accuracy and fine finish. In honing, very thin layers of stock are removed by simultaneously rotating and reciprocating a bonded abrasive stone or stick that is pressed against the surface being honed with lighter force than is typical of grinding.

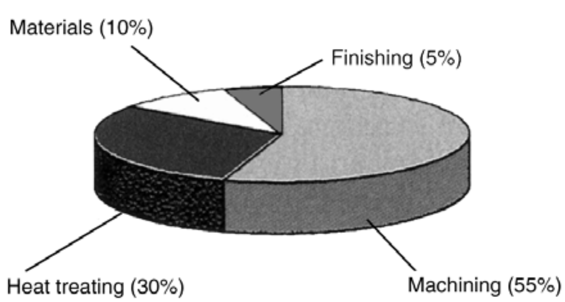

Fig. 24 Typical gear manufacturing costs. Source: Ref 3

Lapping is a polishing operation that uses abrasive pastes to finish the surfaces of gear teeth. Generally a toothed, cast iron lap is rolled with the gear being finished.

Milling is a machining operation which removes the metal between two gear teeth by passing a rotating cutting wheel across the gear blank.

Shaping is a gear cutting method in which the cutting tool is shaped like a pinion. The shaper cuts while traversing across the face width and rolling with the gear blank at the same time.

Shaving is a finishing operation that uses a serrated gear-shaped or rack-shaped cutter to shave off small amounts of metal as the gear and cutter are meshed at an angle to one another. The crossed axes create a sliding motion which enables the shaving cutter to cut.

Skiving is a machining operation in which the cut is made with a form tool with its face so angled that the cutting edge progresses from one end of the workpiece to the other as the tool feeds tangentially past the rotating workpiece.

Casting, Forming, and Forging Processes

Casting is a process of pouring or injecting molten metal into a mold so that the metal solidifies and hardens into the desired shape. Casting is often used to make gear blanks that will have cut teeth. Small gears are frequently cast complete with teeth by the die casting process, which uses a precision mold of tool steel and low-melting-point alloys for the gears.

Stamping is a fast inexpensive method of producing small gears from thin sheets of metal. The metal is sheared by a punching die which stamps through the sheet stock into a mating hole.

Gear rolling is a process which rapidly shapes fine gear teeth or worm threads by high-pressure rolling with a toothed die.

Powder Metallurgy (P/M) Processing. In its most basic and widely used form, the P/M process consists of pressing a powder to the desired shape, followed by heating (sintering) at an elevated temperature below its melting point. There are a number of variations of the P/M process that are applicable to gears (see Fig. 1 in Chapter 7). The P/M process is suitable for high-volume production of small gears. It is not economical for low-to-medium volume production.

Injection molding is a method of forming a plastic to the desired shape by forcing the heatsoftened plastic into a relatively cool cavity (die) under pressure. It is widely used for high-volume production of thermoplastic resin (e.g., acetals and nylons) gears. Often lubricants are added to the thermoplastic material to further improve the inherent lubricity of the material.

Forging. The forging process has long been used to create blanks that will be subsequently shaped into gears by metal removal methods. However, it is increasingly being used for the production of near-net shape and net shape gears for demanding applications where great strength and durability are required. The forging process is carried out hot with metal preheated to a desired temperature under intense pressure until it fills the die cavity. The resultant grain flow which smoothly follows gear tooth contours makes forged gears stronger than those made by other processes.

Alternative or Nontraditional Gear Manufacturing

Although the gear manufacturing processes discussed above are by far the most prevalent methods for gear production, there are a number of other processes that are being used increasingly by the gear industry.

Laser Machining. While sometimes slower than traditional machining techniques, depending on the material, lasers can cut complex shapes such as gears with great precision and very little material waste. This conservation comes from the ability of the computerized-numerically-controlled (CNC) machines controlling the lasers to reuse cutting paths, getting as many gears from a single sheet as possible. Also, the computer control means that laser machining is also low maintenance. The setup and first runs are closely supervised, but the actual production runs don't need any real supervision due to the CNC programming.

Limitations of the laser machining process are as follows:

- Pieces cut with a laser have heat affected zones, areas where the metal is heated beyond a critical transformation point, and recast. These zones are limited, however, to the edges of the cuts—minimizing, but not eliminating heat distortion and the need for further machining. Post production grinding and honing are common.
- Lasers are limited to cutting metals ≤19 mm (≤0.75 in.). Cutting thicker materials requires too much power.
- Lasers are limited to nonreflective or semi-reflective metals. Metals like aluminum and brass that are highly reflective are difficult to cut.
- Lasers are limited, like stamping, to flat forms such as spur gears.

Electrical Discharge Machining (EDM). The EDM process uses electricity to melt or vaporize the material being cut. Many of the attributes and limitations outlined for laser machining are also applicable to EDM.

Abrasive water jet machining is a hydrodynamic machining process that uses a high-velocity stream of water laden with fine abrasive particles as a cutting tool. The process typically produces burr-free edges with heat-affected zones, can easily handle heat treated material, and, unlike lasers, can cut through stacks of material to create multiple parts at the same time, saving time and money. Abrasive waterjets have been used to:

- Cut lapping machine gears made from difficult-to-machine plastic composites
- Titanium rack and pinion components for commercial jet pilot seats
- Process phenolics into machinery gear components
- Cut spring steel into gears with tightly spaced teeth

Inspection

As noted at the bottom of Fig. 23, inspection is an integral part of the gear manufacturing process. As with all manufactured products, gears must be checked to determine whether the resulting product meets design specifications and requirements. Because of the irregular shape of gears and the number of factors that must be measured, such inspection is somewhat difficult. Among the factors to be checked are the linear tooth dimensions (thickness, spacing, depth, and so on), tooth profile, surface roughness, and noise. Several special devices, most of them automatic or semiautomatic, are used for this inspection.

Gear tooth vernier calipers can be used to measure the thickness of gear teeth on the pitch circle. However, inspection is usually done by special machines, which in one or a series of operations check several factors, including eccentricity, variations in circular pitch, variations in pressure angle, fillet interference, and lack of continuous action. The gear is usually mounted and moved in contact with a master gear. The movement of the latter is amplified and recorded on moving charts, as shown in Fig. 25.

Noise level is important in many applications, not only from the standpoint of noise pollution but also as an indicator of probable gear life. Therefore, special equipment for its measurement is quite widely used, sometimes integrated into mass-production assembly lines.

Dimensional variations in gears result in noise, vibration, operational problems, reduced carrying ability, and reduced life. These problems are compounded at higher gear-operating speeds. AGMA has incorporated the critical dimensions of pitch, concentricity, tooth profile, tooth thickness, and tooth surface finish into a number of standards which the interested reader should refer to. Additional information can also be found in Ref 4 and 5.

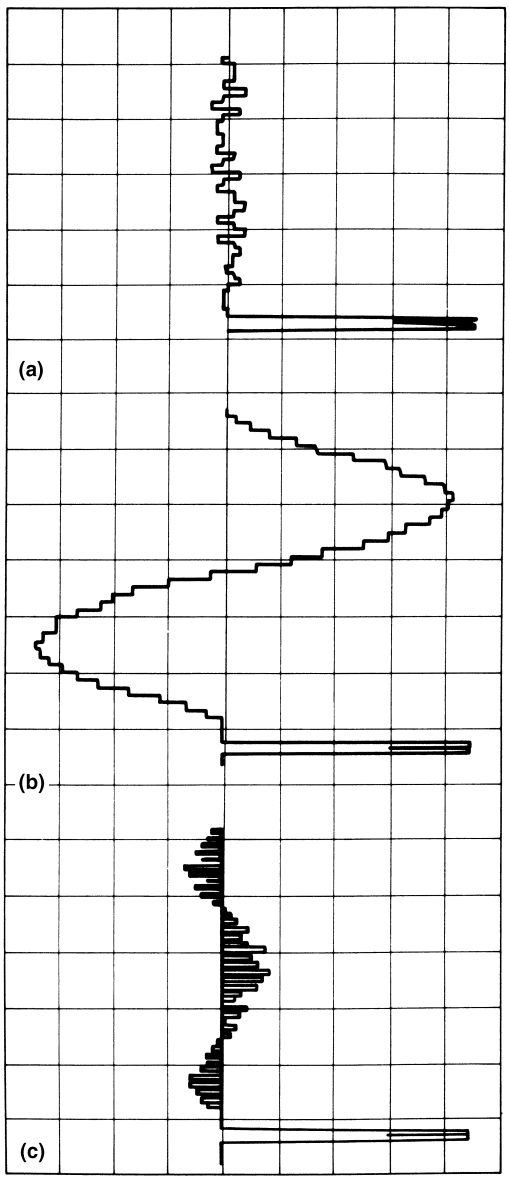

Fig. 25 Typical data obtained on charts generated by automated gear-checking machines. (a) Tooth-to-tooth pitch error. (b) Accumulated pitch error. (c) Spacing error

Heat Treating (Ref 3)

Heat treating is one of the most important steps in the manufacture of precision gearing. Its contribution is vitally important for cost control, durability, and reliability. As shown in Fig. 24, heat treating represents about 30% of a typical gear manufacturing cost. If not properly understood and controlled, it can have a significant impact on all aspects of the gear manufacturing process. This section will briefly review the following heat treating processing steps: prehardening processes, through hardening and case hardening processes, applied energy hardening, and post-hardening processes. More detailed information on these processes can be found in the following chapters:

- Chapter 8, "Through Hardening"
- Chapter 9, "Carburizing"
- Chapter 10, "Nitriding"
- Chapter 11, "Carbonitriding"
- Chapter 12, "Induction and Flame Hardening"

Prehardening Processes

Several heat treatments are normally performed during the gear manufacturing process to prepare the part for the intended manufacturing steps. These are essential to the manufacture of a quality gear.

Annealing consists of heating to and holding at a suitable temperature followed by cooling at an appropriate rate, primarily intended to soften the part and improve its machinability. Supercritical or full annealing involves heating a part above the upper critical temperature (Ac_3), that is the temperature at which austenite begins to transform to ferrite during cooling, and then slowly cooling in the furnace to around 315 °C (600 °F). Intercritical annealing involves heating the part to a temperature above the final transformation temperature (Ac_1), the temperature at which austenite begins to form during heating. Subcritical annealing heats the part to just below the Ac_1 point followed by a slow cool in the furnace. The rate of softening increases rapidly as the annealing temperature approaches the Ac_1 point.

Normalizing involves heating the part above the upper critical temperature and then air cooling outside the furnace to relieve residual stresses in a gear blank and for dimensional stability. Normalizing is often considered from both a thermal and microstructural standpoint. In the thermal sense, normalizing is austenitizing followed by cooling in still or slightly agitated air or nitrogen. In a microstructural sense, normalizing produces a more homogenous structure. A normalized part is very machinable but harder than an annealed part. Normalizing also plays a significant role in the control of dimensional variation during carburizing.

Stress relieving involves heating to a temperature below the lower transformation temperature, as in tempering, holding long enough to reduce residual stress and cooling slowly enough, usually in air, to minimize the development of new residual stresses. Stress relief heat treating is used to relieve internal stresses locked in the gear as a consequence of a manufacturing step.

Through Hardening and Case Hardening

Various heat treatment processes are designed to increase gear hardness. These usually involve heating and cooling and are typically classified as through hardening, case hardening, and hardening by applied energy which will be discussed separately in a subsequent section.

Through or direct hardening refers to heat treatment methods, which do not produce a case. Examples of commonly through hardened gear steels are AISI 1045, 4130, 4140, 4145, 4340, and 8640. It is important to note that hardness uniformity should not be assumed throughout the gear tooth. Since the outside of a gear is cooled faster than the inside, there will be a hardness gradient developed. The final hardness is dependent on the amount of carbon in the steel; the depth of hardness depends on the hardenability of the steel as well as the quench severity.

Through hardening can be performed either before or after the gear teeth are cut. When gear teeth will be cut after the part has been hardened, surface hardness and machinability become important factors especially in light of the fact that machining will remove some or most of the higher hardness material at the surface. The hardness is achieved by heating the material into the austenitic range, typically 815 to 875 °C (1500 to 1600 °F), followed by quenching and tempering.

Case hardening produces a hard, wear resistant case or surface layer on top of a ductile, shock resistant interior, or core. The idea behind case hardening is to keep the core of the gear tooth at a level around 30 to 40 HRC to avoid tooth breakage while hardening the outer surface to increase pitting resistance. The higher the surface hardness value, the greater the pitting resistance. Bending strength increases for surface hardness up to about 50 HRC, after which the increase in bending strength is offset by an increase in notch sensitivity.

Carburizing is the most common of the case hardening methods. A properly carburized gear will be able to handle between 30% to 50% more load than a through hardened gear. Carburizing steels are typically alloy steels with approximately 0.10% to 0.20% carbon. Examples of commonly carburized gear steels include AISI 1018, 4320, 5120, 8620, and 9310 as well as international grades such as 20MnCr5, 16MnCr5, ZF-7B, 20MoCr4, and V2525.

Carburizing can be performed in the temperature range of 800 to 1090 °C (1475 to 2000 °F). Common industry practice today finds the majority of carburizing operations taking place at 870 to 1010 °C (1600 to 1850 °F). Carburizing case depths can vary over a broad range, 0.13 to 8.25 mm (0.005 to 0.325 in.) being typical. However, it is common to use the carbonitriding process for case depths below 0.4 mm (0.015 in.).

Carbonitriding is a modification of the carburizing process, not a form of nitriding. This modification consists of introducing ammonia into the carburizing atmosphere to add nitrogen to the carburized case as it is being produced. Examples of gear steels that are commonly carbonitrided include AISI 1018, 1117, and 12L14.

Typically, carbonitriding is done at a lower temperature than carburizing, or between 700 to 900 °C (1300 to 1650 °F), and for a shorter time. Because nitrogen inhibits the diffusion of carbon, what generally results is a shallower case than is typical for carburized parts. A carbonitrided case is usually between 0.075 to 0.75 mm (0.003 to 0.030 in.) deep.

Nitriding is another surface treatment process that increases surface hardness. Since rapid quenching is not required, dimensional changes are kept to a minimum, which is a major advantage. It is not suitable for all gear materials. One of its limitations is the extremely high surface hardness or "white layer" produced, which has a more brittle nature than the surface produced by carburizing. Despite this, nitriding has proved to be a viable alternative for numerous applications. Commonly nitrided gear steels include AISI 4140, 4150, 4340, 7140, 8640, and AMS 6475 (Nitralloy N).

Nitriding is typically done in the 495 to 565 °C (925 to 1050 °F) range. Three factors that are extremely critical in producing superior and consistent nitrided cases and predictable dimensional change are steel composition, prior structure, and core hardness. Case depth and case hardness properties vary not only with the duration and type of nitriding being performed but are also influenced by these factors. Typically case depths are between 0.20 to 0.65 mm (0.008 to 0.025 in.) and take from 10 to 80 hours to produce.

ACKNOWLEDGMENT

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Chapter 1: Basic Understanding of Gears

References

1. *Gear Nomenclature, Definitions of Terms with Symbols*, ANSI/AGMA 1012-F90, American Gear Manufacturerers Association, 1990

2. L.E. Alban, *Systematic Analysis of Gear Failures*, American Society for Metals, 1985

3. F.J. Otto and D.H. Herring, Gear Heat Treatment: Part I, *Heat Treating Progress*, June 2002, p 55–59

4. D.W. Dudley, *Handbook of Practical Gear Design*, McGraw Hill Book Company, 1984

5. D.P. Townsend, Ed., *Dudley's Gear Handbook: The Design, Manufacture, and Application of Gears*, 2nd ed., McGraw Hill, Inc., 1991

Preview for: *Gear Materials, Properties, and Manufacture,* edited by J.R. Davis, ASM International, 2005
Full digital book available at https://doi.org/10.31399/asm.tb.gmpm.9781627083454

Chapter 2: Gear Tribology and Lubrication

References

1. R. Errichello, The Lubrication of Gears, *Lubrication Engineering*, Jan–April, 1990

2. E.E. Shipley, Gear Failures, *Mach. Des.*, 7 Dec 1967, p 152–162

3. D.W. Dudley, Gear Wear, *Wear Control Handbook*, American Society of Mechanical Engineers

4. P.M. Ku, Gear Failure Modes—Importance of Lubrication and Mechanics, *ASLE Trans.*, Vol 19 (No. 3), 1975, p 239–249 doi: 10.1080/05698197608982799

5. D.J. Wulpi, *Understanding How Components Fail*, American Society for Metals, 1985

6. L.E. Alban, Failures of Gears, *Failure Analysis and Prevention*, Vol 11, 9th ed., *Metals Handbook*, ASM International, 1986, p 586–601

7. D. Godfrey, Recognition and Solution of Some Common Wear Problems Related to Lubrication and Hydraulic Fluids, *Lubr. Eng.*, Feb 1987, p 111–114

8. W.E. Littman, The Mechanism of Contact Fatigue, *Interdisciplinary Approach to the Lubrication of Concentrated Contacts*, SP-237, National Aeronautics and Space Administration, 1970, p 309–377

9. T. Ueno *et al.*, "Surface Durability of Case-Carburized Gears—On a Phenomenon of Grey Staining of Tooth Surface," Paper No. 80-C2/DET-27, American Society of Mechanical Engineers, 1980, p 1–8

10. H. Winter and T. Weiss, "Some Factors Influencing the Pitting, Micropitting (Frosted Areas) and Slow Speed Wear of Surface-Hardened Gears," Paper No. 80-C2/DET-89, American Society of Mechanical Engineers, 1980, p 1–7

11. E.E. Shipley, "Failure Analysis of Coarse-Pitch, Hardened, and Ground Gears," Paper No. P229.26, American Gear Manufacturers Association, 1982, p 1–24

12. S. Tanaka *et al.*"Appreciable Increases in Surface Durability of Gear Pairs with Mirror-Like Finish," Paper No. 84-DET-223, American Society of Mechanical Engineers, 1984, p 1–8

13. A. Milburn, R. Errichello, and D. Godfrey, "Polishing Wear," Paper No. 90 FTM 5, American Gear Manufacturers Association, 1990, p 1–13

14. J.H. Admas and D. Godfrey, Borate Gear Lubricant-EP Film Analysis and Performance, *Lubr. Eng.*, Vol 37 (No. 1), Jan 1981, p 16–21

15. H. Blok, "Les Temperatures de Surface dans les Conditions de Graissage sons Pression Extreme," Second World Petroleum Congress (Paris), June 1937

16. H. Blok, The Postulate about the Constancy of Scoring Temperatures, *Interdisciplinary Approach to the Lubrication of Concentrated Contacts*, SP-237, National Aeronautics and Space Administration, 1970, p 153–248

17. D. Dowson, Elastohydrodynamics, Paper No. 10, *Proc. Inst. Mech. Eng.*, Vol 182, PT3A, 1967, p 151–167 doi: 10.1243/PIME_CONF_1967_182_014_02

18. "Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth," 2001-B88, American Gear Manufacturers Association, 1988

19. M. Akazawa, T. Tejima, and T. Narita, "Full Scale Test of High Speed, High Powered Gear Unit—Helical Gears of 25,000 PS at 200 m/s PLV," Paper No. 80-C2/DET-4, American Society of Mechanical Engineers, 1980

20. R.J. Drago, "Comparative Load Capacity Evaluation of CBN-Finished Gears," Paper No. 88 FTM 8, American Gear Manufacturers Association, Oct 1988

21. "AGMA Standard Specification—Lubrication of Industrial Enclosed Gear Drives," No. 250.04, American Gear Manufacturers Association, Sept 1981

22. "Practice for High Speed Helical and Herringbone Gear Units," No. 421.06, American Gear Manufacturers Association, Jan 1969

23. E.J. Wellauer and G.A. Holloway, Application of EHD Oil Film Theory to Industrial Gear Drives, *J. Eng. Ind. (Trans. ASME)*, Vol 98, Series B (No. 2), May 1976, p 626–634 doi: 10.1115/1.3438951

24. R.J. Drago, *Fundamentals of Gear Design*, Butterworths, 1998

25. L. Akin and D. Townsend, "Study of Lubricant Jet Flow Phenomena in Spur Gears," TMX-71572, National Aeronautics and Space Administration, Oct 1974

26. SCORING+, computer program, GEAR-TECH Software, Inc., Copyright 1985–1992

Selected References

- R.H. Boehringer, Grease, *Friction, Lubrication, and Wear Technology*, Vol 18, *ASM Handbook*, ASM International, 1992, p 123–131

- H.S. Cheng, Lubrication Regimes, *Friction, Lubrication, and Wear Technology*, Vol 18, *ASM Handbook*, ASM International, 1992, p 89–97

- R.S. Fein, Liquid Lubricants, *Friction, Lubrication, and Wear Technology*, Vol 18, *ASM Handbook*, ASM International, 1992, p 81–88

- S.Q.A. Rizvi, Lubricant Additives and Their Functions, *Friction, Lubrication, and Wear Technology*, Vol 18, *ASM Handbook*, ASM International, 1992, p 98–112

- H.E. Sliney, Solid Lubricants, *Friction, Lubrication, and Wear Technology*, Vol 18, *ASM Handbook*, ASM International, 1992, p 113–122

Chapter 3: Ferrous and Nonferrous Alloys

References

1. N.P. Chirons, Ed., *Gear Design and Application*, McGraw-Hill, 1967, p 269–274

2. Hardenability of Steels, *ASM Specialty Handbook: Carbon and Alloy Steels*, J.R. Davis, Ed., ASM International, 1996, p 138–166

3. R.E. Cohen, P.J. Haagensen, D.K. Matlock, and G. Krauss, "Assessment of Bending Fatigue Limits for Carburized Steel," Technical Paper 910140, SAE International, 1991 doi: 10.4271/910140

4. D.V. Doane, Carburized Steel—Update on a Mature Composite, *Carburizing: Processing and Performance*, G. Krauss, Ed., ASM International, 1989, p 169–190

5. H.O. Fuchs and R.I. Stephens, *Metal Fatigue in Engineering*, John Wiley & Sons, 1980

6. R.W. Landgraf and R.H. Richman, Fatigue Behavior of Carburized Steel, *Fatigue of Composite Materials*, STP 569, American Society for Testing and Materials (ASTM), 1975, p 130–144 doi: 10.1520/STP33169S

7. H. Brugger and G. Krauss, Influence of Ductility on the Behavior of Carburizing Steel during Static and Dynamic Bend Testing, *Arch. Eisenhuttenwes.*, Vol 32, 1961, p 529–539 doi: 10.1002/srin.196103243

8. R.E. Cohen, D.K. Matlock, and G. Krauss, Specimen Edge Effects on Bending Fatigue of Carburized Steel, *J. Mater. Eng. Perform.*, Vol 1 (No. 5), 1992, p 695–703 doi: 10.1007/BF02649251

9. D.H. Breen and E.M. Wene, Fatigue in Machines and Structures—Ground Vehicles, *Fatigue and Microstructure*, American Society for Metals, 1979, p 57–99

10. Z. Zurn and C. Razim, On the Fatigue Strength of Case Hardened Parts, *Carburizing: Processing and Performance*, G. Krauss, Ed., ASM International, 1989, p 239–248

11. M.B. Slane, R. Buenneke, C. Dunham, M. Semenek, M. Shea, and J. Tripp, "Gear Single Tooth Bending Fatigue," Technical Paper 821042, SAE International, 1982

12. D. Medlin, G. Krauss, D.K. Matlock, K. Burris, and M. Slane, "Comparison of Single Gear Tooth and Cantilever Beam Bend Fatigue Testing of Carburized Steel," Technical Paper 950212, SAE International, 1995 doi: 10.4271/950212

13. R.S. Hyde, R.E. Cohen, D.K. Matlock, and G. Krauss, "Bending Fatigue Crack Characterization and Fracture Toughness of Gas Carburized SAE 4320 Steel," Technical Paper 920534, SAE International, 1992 doi: 10.4271/920534

14. M.A. Zaccone, J.B. Kelley, and G. Krauss, Strain Hardening and Fatigue of Simulated Case Microstructures in Carburized Steel, *Carburizing: Processing and Performance*, G. Krauss, Ed., ASM International, 1989, p 249–265

15. M.M. Shea, "Impact Properties of Selected Gear Steels," Technical Paper 780772, SAE International, 1978 doi: 10.4271/780772

16. G. Krauss, The Relationship of Microstructure to Fracture Morphology and Toughness of Hardened Hypereutectoid Steels, *Case Hardened Steels: Microstructure and Residual Stress Effects*, TMS/AIME, 1984, p 33–56

17. R.S. Hyde, "Quench Embrittlement and Intergranular Oxide Embrittlement: Effects on Bending Fatigue Initiation of Gas-Carburized Steel," Ph.D. dissertation, Colorado School of Mines, 1994

18. L. Magnusson and T. Ericsson, Initiation and Propagation of Fatigue Cracks in Carburized Steel, *Heat Treatment '79*, The Metals Society, London, 1979, p 202–206

19. J.L. Pacheco and G. Krauss, Microstructure and High Bending Fatigue Strength in Carburized Steel, *J. Heat Treat.*, Vol 7 (No. 2), 1989, p 77–86 doi: 10.1007/BF02833192

20. K.A. Erven, D.K. Matlock, and G. Krauss, Effect of Sulfur on Bending Fatigue of Carburized Steel, *J. Heat Treat.*, Vol 9, 1991, p 27–35 doi: 10.1007/BF02833244

21. G. Krauss, The Microstructure and Fracture of a Carburized Steel, *Metall. Trans. A*, Vol 9, 1978, p 1527–1535 doi: 10.1007/BF02661935

22. R.S. Hyde, G. Krauss, and D.K. Matlock, Phosphorus and Carbon Segregation: Effects on Fatigue and Fracture of Gas-Carburized Modified 4320 Steel, *Metall. Trans. A*, Vol 25, 1994, p 1229–1240 doi: 10.1007/BF02652297

23. G. Krauss, *Steels: Heat Treatment and Processing Principles*, ASM International, 1990

24. G. Krauss, Heat Treated Martensitic Steels: Microstructural Systems for Advanced Manufacture, *ISIJ Int.*, Vol 35 (No. 4), 1995, p 349–359 doi: 10.2355/isijinternational.35.349

25. K.A. Erven, D.K. Matlock, and G. Krauss, Bending Fatigue and Microstructure of Gas-Carburized Alloy Steels, *Mat. Sci. Forum*, Vol 102– 104, 1992, p 183–198 doi: 10.4028/www.scientific.net/MSF.102-104.183

26. R.E. Cohen, G. Krauss, and D.K. Matlock, "Bending Fatigue Performance of Carburized 4320 Steel," Technical Paper 930963, SAE International, 1993 doi: 10.4271/930963

27. B. Thoden and J. Grosch, Crack Resistance of Carburized Steel under Bend Stress, *Carburizing: Processing and Performance*, G. Krauss, Ed., ASM International, 1989, p 303–310

28. R.S. Hyde, D.K. Matlock, and G. Krauss, "The Effect of Reheat Treatments on Fatigue and Fracture of Carburized Steel," Technical Paper 940788, SAE International, 1994 doi: 10.4271/940788

29. S. Gunnarson, Structure Anomalies in the Surface Zone of Gas-Carburized Case-Hardened Steel, *Met. Treat. Drop Forg.*, Vol 30, 1963, p 219–229

30. T. Naito, H. Ueda, and M. Kikuchi, Fatigue Behavior of Carburized Steel with Internal Oxides and Nonmartensitic Microstructures Near the Surface, *Metall. Trans. A*, Vol 15, 1984, p 1431–1436 doi: 10.1007/BF02648572

31. W.E. Dowling Jr., W.T. Donlon, W.B. Copple, and C.V. Darragh, Fatigue Behavior of Two Carburized Low Alloy Steels, *1995 Carburizing and Nitriding with Atmospheres*, J. Grosch, J. Morral, and M. Schneider, Ed., ASM International, 1995, p 55–60

32. C. Razim, Uber den Einfluss von Restaustenit auf des Festigkeitsverhalten Einsatzgeharteter Probenkorper bei Schwin-gender Bean-spruchung, *Harterei-Tech. Mitt.*, Vol 23, 1968, p 1–8

33. R.H. Richman and R.W. Landgraf, Some Effects of Retained Austenite on the Fatigue Resistance of Carburized Steel, *Metall. Trans. A*, Vol 6, 1975, p 955–964 doi: 10.1007/BF02661347

34. M. Zaccone and G. Krauss, Elastic Limit and Microplastic Response of Hardened Steels, *Metall. Trans. A*, Vol 24, 1993, p 2263–2277 doi: 10.1007/BF02648600

35. G.B. Olson, Transformation Plasticity and the Stability of Plastic Flow, *Deformation, Processing, and Structure*, G. Krauss, Ed., ASM International, 1984, p 391–424

36. Final Report, Advanced Rotorcraft Transmission Program, National Aeronautics and Space Administration, Cleveland, Ohio

37. R.J. Johnson, The Role of Nickel in Carburizing Steels, *Met. Eng. Quart.*, Vol 15 (No. 3), 1975, p 1–8

38. K.D. Jones and G. Krauss, Effects of High-Carbon Specimen Corners on Microstructure and Fatigue of Partial Pressure Carburized Steels, *Heat Treatment '79*, The Metals Society, London, 1979, p 188–193

39. C. Kim, D.E. Diesburg, and R.M. Buck, Influence of Sub-Zero and Shot-Peening Treatment on Impact and Fatigue Fracture Properties of Case-Hardened Steels, *J. Heat Treat.*, Vol 2 (No. 1), 1981, p 43–53 doi: 10.1007/BF02833073

40. M.A. Panhans and R.A. Fournelle, High Cycle Fatigue Resistance of AISI E9310 Carburized Steel with Two Different Levels of Surface Retained Austenite and Surface Residual Stress, *J. Heat Treat.*, Vol 2 (No. 1), 1981, p 55–61 doi: 10.1007/BF02833074

41. J. Grosch and O. Schwarz, Retained Austenite and Residual Stress Distribution in Deep Cooled Carburized Microstructures, *1995 Carburizing and Nitriding with Atmospheres*, J. Grosch, J. Morral, and M. Schneider, Ed., ASM International, 1995, p 71–76

42. M.G. Mendiratta, J. Sasser, and G. Krauss, Effect of Dissolved Carbon on Microcracking in Martensite of an Fe-1.39 pct C Alloy, *Metall. Trans.*, Vol 3, 1972, p 351–353 doi: 10.1007/BF02680620

43. R.P. Brobst and G. Krauss, The Effect of Austenite Grain Size on Microcracking in Martensite of an Fe-1.22C Alloy, *Metall. Trans.*, Vol 5, 1975, p 457–462 doi: 10.1007/BF02644114

44. L.J. Ebert, The Role of Residual Stresses in the Mechanical Performance of Case Carburized Steel, *Metall. Trans. A*, Vol 9, 1978, p 1537–1551 doi: 10.1007/BF02661936

45. D.P. Koistinen, The Distribution of Residual Stresses in Carburized Steels and Their Origin, *Trans. ASM*, Vol 50, 1938, p 227–241

46. B. Liscic, State of the Art in Quenching, *Quenching and Carburizing*, The Institute of Materials, London, 1993, p 1–32

47. A.K. Hellier, M.B. McGirr, S.H. Alger, and M. Stefulji, Computer Simulation of Residual Stresses during Quenching, *Quenching and Carburizing*, The Institute of Materials, London, 1993, p 127–138

48. G. Totten, Ed., *Quenching and Distortion Control*, ASM International, 1992

49. G. Parrish and G.S. Harper, *Production Gas Carburizing*, Pergamon Press Inc., 1985 doi: 10.1016/B978-0-08-027312-9.50004-3

50. G. Krauss, Microstructure, Residual Stresses and Fatigue of Carburized Steels, *Quenching and Carburizing*, The Institute of Materials, London, 1993, p 205–225

51. R.P. Garibay and N.S. Chang, Improved Fatigue Life of a Carburized Gear by Shot Peening Parameter Optimization, *Carburizing: Processing and Performance*, G. Krauss, Ed., ASM International, 1989, p 283–289

52. H. Swahn, P.C. Becker, and O. Vingsbo, Martensite Decay during Rolling Contact Fatigue in Ball Bearings, *Metall. Trans. A*, Vol 7, 1976, p 1099–1110 doi: 10.1007/BF02656592

53. J.A. Martin, S.F. Borgese, and A.D. Eberhardt, Microstructural Alterations of Roller-Bearing Steel Undergoing Cyclic Stresses, *J. Basic Eng.*, 1966, p 555–567 doi: 10.1115/1.3645902

54. V. Bhargava, G.T. Hahn, and C.A. Rubin, Rolling Contact Deformation, Etching Effects, and Failure of High Strength Bearing Steel, *Metall. Trans. A*, Vol 21, 1990, p 1921–1931 doi: 10.1007/BF02647240

55. C.A. Stickels, Rolling Contact Fatigue Tests of 52100 Bearing Steel Using a Modified NASA Ball Test Rig, *Wear*, Vol 98, 1984, p 199–210 doi: 10.1016/0043-1648(84)90227-8

56. L. Kiessling, Rolling-Contact Fatigue of Carburized and Carbonitrided Steels, *Heat Treat. Met.*, Vol 7 (No. 4), 1980, p 97–101

57. C.V. Darragh, Engineered Gear Steels: A Review, *Gear Technology*, November/December, 2002, p 33–40

58. C.A. Stickels, Carburizing, *Friction, Lubrication, and Wear Technology*, Vol 18, *ASM Handbook*, ASM International, 1992, p 873–877

59. *Modern Carburized Nickel Alloy Steels, Reference Book Series 11,005*, Nickel Development Institute, 1989

60. C. Razim, “Some Facts and Considerations of Trends in Gear Steels for the Automotive Industry,” *Alloys for the Eighties*, Climax Molybdenum Company, 1980, p 9

61. T.B. Cameron, D.E. Diesburg, and C. Kim, Fatigue and Overload Fracture of a Carburized Case, *J. Metals*, May 1983 doi: 10.1007/BF03338322

62. Y.E. Smith and D.E. Diesburg, Fracture Resistance in Carburizing Steels, Parts I, II, III, *Met. Prog.*, May, June, July 1979

63. D.E. Diesburg, “High-Hardenability Carburizing Steels for Rock Bits,” *Micon 78: Optimization of Processing, Properties, and Service Performance Through Microstructural Control*, STP 672, *ASTM*, 1979

64. *Steel Castings Handbook*, 6th ed., M. Blair and T.L. Stevens, Ed., Steel Founders’ Society of America and ASM International, 1995, p 18–8

65. *Dudley’s Gear Handbook*, 2nd ed., D.P. Townsend, Ed., McGraw-Hill, Inc., p 8–27

Chapter 4: Plastics

References

1. C.E. Adams, *Plastics Gearing: Selection and Application*, Marcel Dekker, 1986

2. *Materials for Plastic Gears*, AGMA 920-A01, American Gear Manufacturers Association, 2001

3. M.I. Kohan, Polyamides (PA), *Engineering Plastics*, Vol 2, *Engineered Materials Handbook*, ASM International, 1988, p 124–127

4. D.P. Townsend, Ed., *Dudley's Gear Handbook*, Second Edition, McGraw Hill, Inc. 1991, p 17.2

Chapter 5: Machining, Grinding, and Finishing

References

1. W.N. Ault, Grinding Equipment and Processes, *Machining*, Vol 16, *Metals Handbook*, ASM International, 1989, p 430–452 doi: 10.31399/asm.hb.v16.a0002151

2. K. Subramanian, Superabrasives, *Machining*, Vol 16, *Metals Handbook*, ASM International, 1989, p 453–471 doi: 10.31399/asm.hb.v16.a0002152

3. M. Field, J.F. Kahles, and W.P. Koster, Surface Finish and Surface Integrity, *Machining*, Vol 16, *Metals Handbook*, 9th ed., ASM International, 1989, p 19–36 doi: 10.31399/asm.hb.v16.a0002119

4. T.L. Krantz, M.P. Alanou, H.P. Evans, and R.W. Snidle, Surface Fatigue Lives of Case-Carburized Gears With an Improved Surface Finish, *J. Tribology* (Trans. ASME), October 2001, Vol 123, p 709–716 doi: 10.1115/1.1387036

5. R.W. Snidle, H.P. Evans, M.P. Alanou, The Effect of Superfinishing on Gear Tooth Profile, Report AD-327916, June 1997, available from the *Defense Technical Information Center (DTIC), the National Technical Information Service (NTIS)*, or the NASA Scientific and Technical Information Center (http://www.grc.nasa.gov)

Selected References

• *Dudley's Gear Handbook: The Design, Manufacture, and Application of Gears*, 2nd ed., D.P. Townsend, Ed., McGraw-Hill Inc., 1991

• D.W. Dudley, *Handbook of Practical Gear Design*, McGraw-Hill Book Company, 1984

Chapter 6: Casting, Forming, and Forging

References

1. T.T. Krenzer and J.W. Coniglio, Gear Manufacture, *Machining*, Vol 16, *ASM Handbook*, ASM International, 1989, p 330–355 doi: 10.31399/asm.hb.v16.a0002145

2. J.G. Bralla, *Handbook of Product Design for Manufacturing*, Vol 16, McGraw-Hill Book Company, 1986, p 355

3. M. Blair and T.L. Stevens, Ed., *Steel Castings Handbook*, Sixth Edition, Steel Founders' Society and ASM International, 1995, p 2–34

4. D.W. Dudley, Gear-Manufacturing Methods, *Handbook of Practical Gear Design*, McGraw-Hill Book Company, p 5.86

5. C. Cooper, Alternative Gear Manufacturing, *Gear Technol.*, July/Aug 1998, p 9–16 doi: 10.1016/S0262-1762(99)80412-X

6. D.P. Townsend, Ed., Gears Made by Dies, *Dudley's Gear Handbook: The Design, Manufacture, and Application of Gears*, Second Edition, McGraw Hill Book Company, 1992, p 17.1–17.21

7. D.J. Kuhlmann and P.S. Raghupathi, Manufacturing of Forged and Extruded Gears, *Gear Technol.*, July/Aug 1990, p 36–45

8. T. Russell and L. Danis, Precision Flow Forged Gears, *Gear Manufacture and Performance*, American Society for Metals, 1974, p 229–239

Chapter 7: Powder Metallurgy

References

1. P.W. Lee, Press and Sintered Parts and Their Applications, *Powder Metallurgy Applications Advantages and Limitations*, Erhard Klar, Ed., American Society for Metals, 1983, p 82

2. S.D.K. Saheb and K. Gopinath, Powder Metallurgy Gears—A Brief Review, *Powder Metall. Sci. Technol.*, Vol 1 (No. 4), July 1990, p 43–66

3. S.D.K. Saheb and K. Gopinath, Tooling for Powder Metallurgy Gears, *Powder Metall. Sci. Technol.*, Vol 2 (No. 3), April 1991, p 25–42

4. *Met. Powder Rep.*, Vol 43, 1988, p 536

5. W. Konig, G. Rober, K. Vossen, and M. Stromgren, Powder Forging of Helical Gears for Car Manual Gear Boxes—Concept and Properties, *Met. Powder Rep.*, Vol 45 (No. 4), 1990, p 269–273 doi: 10.1016/S0026-0657(10)80053-0

6. *Powder Metallurgy Design Manual*, Metal Powder Industries Federation, 1994, p 193

7. G. Parrish and G.S. Harper, *Production Gas Carburizing*, Pergamon, 1985, p 20 doi: 10.1016/B978-0-08-027312-9.50004-3

8. *Gear Design Manufacturing and Inspection Manual*, SAE No. 841083, Society of Automotive Engineers, 1990, p 46

9. "AGMA Standard for Rating the Strength of Spur Gear Teeth," AGMA 220.02, American Gear Manufacturers' Association, 1966

10. "AGMA Standard for Rating the Strength of Helical and Herringbone Gear Teeth," AGMA 221.02, American Gear Manufacturers' Association, 1965

11. "AGMA Standard for Rating the Strength of Straight Bevel and Zero Bevel Gear Teeth, AGMA 222.02, American Gear Manufacturers' Association, 1964

12. "AGMA Standard for Surface Durability of Spur Gear Teeth," AGMA 210.02, American Gear Manufacturers' Association, 1965

13. "AGMA Standard for Surface Durability of Helical and Herringbone Gear Teeth," AGMA 211.02, American Gear Manufacturers' Association, 1969

14. "AGMA Standard for Surface Durability Formulas for Straight Bevel and Zero Bevel Gear Teeth," AGMA 212.02, American Gear Manufacturers' Association, 1964

15. T. Prucher and H. Sanderow, Surface Fatigue of P/M Alloys, *Characterization, Testing, and Quality Control*, Vol 2, *Advances in Powder Metallurgy and Particulate Materials*, Metal Powder Industries Federation, 1994, p 99–111

16. R. Gnanamoorthy and K. Gopinath, Surface Durability Studies on As-Sintered Low Alloy Steel Gears, *Advances in Powder Metallurgy and Particulate Materials—1992*, Vol 6, Metal Powder Industries Federation, 1992, p 237–250

17. W. Smith, Ferrous Based Powder Metallurgy Gears, *Gear Manufacture and Performance*, American Society for Metals, 1974, p 257–269

Selected References

• AGMA & MPIF Develop Standards, Information Sheet for Powder Metal Gears, *Gear Technol., J. Gear Manuf.*, Sept/Oct 1996

• R. Moderow, Gear Inspection and Measurement, *Gear Technol., J. Gear Manuf.*, July/Aug 1992

• MPIF Standard 35, *Material Standards for P/M Structural Parts*, Metal Powder Industries Federation, 1997

• *Powder Metallurgy Design Manual*, 2nd ed., Metal Powder Industries Federation, 1995

• *Powder Metallurgy Design Solutions*, Metal Powder Industries Federation, 1993

• H. Sanderow, Powder Metal Gear Design and Inspection, *Gear Technol., J. Gear Manuf.*, Sept/Oct 1996

• G. Shturtz, The Beginner's Guide to Powder Metal Gears, *Gear Technol., J. Gear Manuf.*, Sept/Oct 1995

Chapter 8: Through Hardening

Selected References

- C.E. Bates, G.E. Totten, and R.L. Brennan, Quenching of Steel, *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 67–120

- B.L. Bramfitt and A.K. Hingwe, Annealing of Steel, *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 42–55

- T. Ruglic, Normalizing of Steel, *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 35–41

- M. Schmidt and K. Rohrbach, Heat Treating of Maraging Steels, *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 219–228

- M. Wisti and M. Hingwe, Tempering of Steel, *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 121–136

Chapter 9: Carburizing

References

1. D.H. Herring, Pros and Cons of Atmosphere and Vacuum Carburizing, *Ind. Heat.*, Jan 2002, p 45–48

2. J.R. Davis, Ed., Hardenability of Steels, *ASM Specialty Handbook: Carbon and Alloy Steels*, ASM International, 1996, p 138–166

3. D.W. Dudley, *Handbook of Practical Gear Design*, McGraw-Hill Book Company, 1984, p 4.13

4. J.R. Davis, Ed., Gas Carburizing, *Surface Hardening of Steels: Understanding the Basics*, ASM International, 2002, p 17–89

5. G.F. Vander Voort, Ed., Metallography and Microstructures of Case-Hardening Steel, *Metallography and Microstructures*, Vol 9, *ASM Handbook*, ASM International, 2004, p 627–643 doi: 10.31399/asm.hb.v09.a0003762

6. *Gear Materials and Heat Treatment Manual*, ANSI/AGMA 2004-B89, American Gear Manufacturers Association, 1989, p 48

7. F.J. Otto and D.H. Herring, Gear Heat Treatment, Part II, *Heat. Treat. Prog.*, July/Aug 2002, p 27–31

8. G.D. Lindell, D.H. Herring, D.J. Breuer, and B.S. Matlock, Atmosphere versus Vacuum Carburizing, *Heat Treat. Prog.*, Nov 2001, p 33–41

9. W.J. Titus, Considerations when Choosing a Carburizing Process: Traditional Batch Atmosphere Carburizing versus Vacuum and Ion Carburizing, *Ind. Heat.*, Sept 1987

10. B. Edenhofer, Overview of Advances in Atmosphere and Vacuum Heat Treatments, *Heat Treat. Met.*, Vol 4, 1998, and Vol 1, 1999

Chapter 10: Nitriding

References

1. D.W. Dudley, Gear Materials, *Handbook of Practical Gear Design*, McGraw-Hill Book Company, 1984, p 4.1–4.61

2. Gas Nitriding, *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 387–409

3. R. Errichello and D.R. McVittie, Predicting Gear Life with Miner's Rule, *Power Transmission Design*, Vol 31 (No. 3), March 1989, p 33–38

4. G.J. Tymowski, W.K. Liliental, and C.D. Morawski, Typical Nitriding Faults and Their Prevention Through the Controlled Nitriding Process, *Ind. Heat.*, Jan 1995, p 39–44

5. G.J. Tymowski, W.K. Liliental, and C.D. Morawski, Take the Guesswork Out of Nitriding, *Adv. Mater. Process.*, Dec 1994, p 52–54

Selected References

• Plasma (Ion) Nitriding, *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 420–424

• D. Pye, Nitriding Techniques and Methods, *Steel Heat Treatment Handbook*, G.E. Totten and M.A.H. Howes, Ed., Marcel Dekker 1997, p 721–764

• D. Pye, *Practical Nitriding and Ferritic Nitrocarburizing*, ASM International, 2003

Preview for: *Gear Materials, Properties, and Manufacture*, edited by J.R. Davis, ASM International, 2005
Full digital book available at https://doi.org/10.31399/asm.tb.gmpm.9781627083454

Chapter 11: Carbonitriding

Reference

1. D.H. Herring, Comparing Carbonitriding and Nitrocarburizing, *Heat Treat. Prog.*, April/May 2002, p 17–19

Selected References

• R. Davies and C.G. Smith, A Practical Study of the Carbonitriding Process, *Met. Prog.*, Vol 114 (No. 4), 1978, p 40–53

• J. Dossett, Carbonitriding, *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 376–386

Chapter 12: Induction and Flame Hardening

Selected References

• R.E. Haimbaugh, *Practical Induction Heat Treating*, ASM International, 2001

• P.A. Hassell and N.V. Ross, Induction Heat Treating of Steel, *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 164–202

• T. Ruglic, Flame Hardening, *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 268–285

• S.L. Semiatin and D.E. Stutz, *Induction Heat Treatment of Steel*, American Society for Metals, 1986

• S. Zinn and S.L. Semiatin, *Elements of Induction Heating: Design, Control, and Applications*, ASM International, 1988 doi: 10.31399/asm.tb.eihdca.9781627083416

Chapter 13: Gear Failure Modes and Analysis

References

1. L.E. Alban, *Systematic Analysis of Gear Failures*, American Society for Metals, 1985

2. *Appearance of Gear Teeth—Terminology of Wear and Failure*, ANSI/AGMA 1010-E95, American Gear Manufacturers Association, 1995

3. R. Errichello, Friction, Lubrication, and Wear of Gears, *Friction, Lubrication, and Wear Technology*, Vol 18, *ASM Handbook*, ASM International, 1992, p 535–545

4. D.R. McPherson and S.B. Rao, Mechanical Testing of Gears, *Mechanical Testing and Evaluation*, Vol 8, *ASM Handbook*, ASM International, 2000, p 861–872 doi: 10.31399/asm.hb.v08.a0003327

5. R.S. Hyde, Contact Fatigue of Hardened Steel, *Fatigue and Fracture*, Vol 19, *ASM Handbook*, ASM International, 1996, p 691–703 doi: 10.31399/asm.hb.v19.a0002401

6. W.R. Scott, Myths and Miracles of Gear Coatings, *Gear Technology*, July/Aug 1999, p 35–44

7. R. Errichello, Tutorial: How to Analyze Gear Failures, *Practical Failure Analysis*, Vol 2 (No. 6), December 2002, p 8–16 doi: 10.1007/BF02715492

8. B.A. Miller, Overload Failures, *Failure Analysis and Prevention*, Vol 11, *ASM Handbook*, 2002, p 671–699 doi: 10.31399/asm.hb.v11.a0003543

Selected References

• R. Errichello, "Analysis Techniques End Gear Damage," *Power Transmission Design*, March 1995, 37(3), p 23–26

• R. Errichello and J. Muller, "How to Analyze Gear Failures," *Power Transmission Design*, March 1994, 36(3), p 35–40

Chapter 14: Fatigue and Life Prediction

References

1. D.W. Dudley, *The Handbook of Practical Gear Design*, Technomics Publishing Co., Inc., Lancaster, PA, 1994

2. *Fundamental Rating Factors and Calculation Methods for Involute and Helical Gear Teeth*, ANSI/AGMA 2001-C95, American Gear Manufacturers Association

Selected References

Fatigue of Gears

• B. Abersek, J. Flasker, and J. Balic, Theoretical Model for Fatigue Crack Propagation on Gears, *Conf. Proc. Localized Damage III: Computer-Aided Assessment and Control*, Computational Mechanics Publications, Billerica, MA, 1994, p 63–70

• A.Y. Attia, Fatigue Failure of Gears of Circular-Arc Tooth-Profile, *J. Tribol.*, Vol 112 (No. 3), 1990, p 453–459 doi: 10.1115/1.2920281

• G.P. Cavallaro *et al.*, Bending Fatigue and Contact Fatigue Characteristics of Carburized Gears, *Surf. Coat. Technol.*, Vol 71 (No. 2), 1995, p 182–192 doi: 10.1016/0257-8972(94)01019-F

• G. Dalpiaz and U. Meneghetti, Monitoring Fatigue Cracks in Gears, *Nondestr. Test. Eval. Int.*, Vol 24 (No. 6), 1991, p 303–306 doi: 10.1016/0963-8695(91)90003-L

• J. Flasker and B. Abersek, Determination of Plastification of Crack Tip of Short and Long Fatigue Crack on Gears, *Conf. Proc. Computational Plasticity: Fundamentals and Applications*, Pineridge Press Ltd., Mumbles, Swansea, U.K., 1992, p 1585–1595

• Y. Jia, Analysis and Calculation of Fatigue Loading of Machine Tool Gears, *Int. J. Fatigue*, Vol 13 (No. 6), 1991, p 483–487 doi: 10.1016/0142-1123(91)90484-G

• B. Jiang and E.A. Shao, Rapid Method for Measurement of Rolling Contact Fatigue Limit of Case-Hardened Gear Materials, *ASTM J. Test. Eval.*, Vol 18 (No. 5), 1990, p 328–331 doi: 10.1520/JTE12494J

• B. Jiang, X. Zheng, and M. Wang, Calculation for Rolling Contact Fatigue Life and Strength of Case-Hardened Gear Materials by Computer, *ASTM J. Test. Eval.*, Vol 21 (No. 1), 1993, p 9–13 doi: 10.1520/JTE11735J

• B. Jiang, X. Zheng, and L. Wu, Estimate by Fracture Mechanics Theory for Rolling Contact Fatigue Life and Strength of Case-Hardened Gear Materials with Computer, *Eng. Fract. Mech.*, Vol 39 (No. 5), 1991, p 867–874 doi: 10.1016/0013-7944(91)90192-4

• G. Mesnard, Super Puma MK II: Rotor and Gearbox Fatigue, *Conf. Proc. ICAF '91: Aeronautical Fatigue—Key to Safety and Structural Integrity*, Ryoin Co., Tokyo, 1991, p 195–215

• M. Nakamura *et al.*, Effects of Alloying Elements and Shot Peening on Fatigue Strength of Gears, *Kobelco Technol. Rev.*, No. 16, 1993, p 14–19

• Y. Obata *et al.*, Evaluation of Fatigue Crack Growth Rate of Carburized Gear by Acoustic Emission Technique, *Acoustic Emission: Current Practice and Future Directions*, STP 1077, *ASTM*, 1989, p 261–270 doi: 10.1520/STP19099S

• Y. Okada *et al.*, Fatigue Strength Analysis of Carburized Transmission Gears, *JSAE Rev.*, Vol 11 (No. 3), 1990, p 82–84

• W. Pizzichil, Testing Gear Teeth for Low-Cycle Fatigue and Static Bending Strength, *Heat Treating*, Vol 24 (No. 2), 1992, p 14–20

• H.J. Rose, Vibration Signature and Fatigue Crack Growth Analysis of a Gear Tooth Bending Fatigue Failure, *Conf. Proc. Current Practices and Trends in Mechanical Failure Prevention*, Vibration Institute, Willowbrook, IL, p 235–245

• M. Roth and K. Sander, Fatigue Failure of a Carburized Steel Gear from a Helicopter Transmission, *Handbook of Case Histories in Failure Analysis*, Vol 1, ASM International, 1992, p 228–230 doi: 10.31399/asm.fach.v01.c9001077

• G.M. Tanner and J.R. Harty, Contact Fatigue Failure of a Bull Gear, *Handbook of Case Histories in Failure Analysis*, Vol 2, ASM International, 1993, p 39–44 doi: 10.31399/asm.fach.v02.c9001300

• D.P. Townsend, "Improvement in Surface Fatigue Life of Hardened Gears by High-Intensity Shot Peening," TM-105678, National Aeronautics and Space Administration, 1992 doi: 10.1115/DETC1992-0082

• D.P. Townsend and J. Shimski, "Evaluation of Advanced Lubricants for Aircraft Applications Using Gear Surface Fatigue Tests," TM-104336, National Aeronautics and Space Administration, 1991 doi: 10.2514/6.1991-1907

• V.I. Tsypak, Fretting Corrosion and Fatigue of Gears, *Mater. Sci. (Russia)*, Vol 29 (No. 6), 1993, p 680–681 doi: 10.1007/BF00561649

• J.-G. Wang, Z. Feng, and J.-C. Zhou, Effect of the Morphology of Carbides in the Carburizing Case on the Wear Resistance and the Contact Fatigue of Gears, *J. Mater. Eng. (China)*, Dec 1989, p 35–40

• T.P. Wilks *et al.*, Conditions Prevailing in the Carburising Process and Their Effect on the Fatigue Properties of Carburised Gears, *J. Mater. Process. Technol.*, Vol 40 (No. 1–2), 1994, p 111–125 doi: 10.1016/0924-0136(94)90481-2

• J.J. Zakrajsek, D.P. Townsend, and H.J. Decker, An Analysis of Gear Fault Detection Methods as Applied to Pitting Fatigue Failure Data, *Conf. Proc. The Systems Engineering Approach to Mechanical Failure Prevention*, Vibration Institute, Willowbrook, IL, p 199–208

Gear Durability and Failure

• J.W. Blake and H.S. Cheng, A Surface Pitting Life Model for Spur Gears, Part II: Failure Probability Prediction, *J. Tribol.*, Vol 113 (No. 4), 1991, p 719–724 doi: 10.1115/1.2920684

• R. Gnanamoorthy and K. Gopinath, Surface Durability Studies on As-Sintered Low Alloy Steel Gears, *Non-Ferrous Materials*, Vol 6, *Advances in Powder Metallurgy & Particulate Materials*, Metal Powder Industries Federation, 1992, p 237–250

• G.M. Goodrich, Failure of Four Cast Steel Gear Segments, *Handbook of Case Histories in Failure Analysis*, Vol 2, ASM International, 1993, p 45–52 doi: 10.31399/asm.fach.v02.c9001301

• C. Madhavan and K. Gopinath, Surface Durability of Through-Hardened P/M Gears, *Powder Met. Sci. Technol.*, Vol 2 (No. 4), 1991, p 30–44

• T. Nakatsuji, A. Mori, and Y. Shimotsuma, Pitting Durability of Electrolytically Polished Medium Carbon Steel Gears, *Tribol. Trans.*, Vol 38 (No. 2), 1995, p 223–232 doi: 10.1080/10402009508983399

• H.V. Somasundar and R. Krishnamurthy, Surface Durability of HSLA Steel Gears, *Conf. Proc. Ninth National Conference on Industrial Tribology*, Central Machine Tool Institute, Bangalore, India, 1991, p M87–M95

• Y.L. Su, J.S. Lin, and S.K. Hsieh, The Tribological Failure Diagnosis of Spur Gear by an Expert System, *Wear*, Vol 166 (No. 2), 1993, p 187–196 doi: 10.1016/0043-1648(93)90261-J

• A. Verma and R.K. Sidhu, Failure Investigation of Gears, *Tool and Alloy Steels*, Vol 27 (No. 6), 1993, p 157–160

• K. Wozniak, Worm Gears of Increased Durability, *Archiwum Budowy Maszyn*, Vol 38 (No. 1), 1991, p 5–13

Chapter 15: Mechanical Testing

References

1. E.E. Shipley, “Failure Modes in Gears,” presented at Forum on Gear Manufacture and Performance, 19 Oct 1973 (Detroit), American Society of Mechanical Engineers

2. D.W. Dudley, Gear Wear, *Wear Control Handbook*, M. Peterson and W. Winer, Ed., American Society of Mechanical Engineers, 1980

3. G. Niemann and H. Winter, Getriebeschäden und Abhilfe, Entwicklungstendenzen, *Maschinen-elemente*, Vol 2, 2nd ed., Springer-Verlag (Berlin), 1983

4. “Appearance of Gear Teeth—Terminology of Wear and Failure,” ANSI/AGMA 1010-E95, American National Standards Institute/American Gear Manufacturers Association

5. R. Errichello, Friction, Lubrication, and Wear of Gears, *Friction, Lubrication, and Wear Technology*, Vol 18, *ASM Handbook*, ASM International, 1992, p 535–545

6. L. Alban, *Systematic Analysis of Gear Failures*, American Society for Metals, 1985

7. A.P. Boresi and O.M. Sidebottom, *Advanced Mechanics of Materials*, 4th ed., John Wiley & Sons, 1985

8. W. Lewis, Investigation of the Strength of Gear Teeth, *Proc. Eng. Club*, Philadelphia, PA, 1893

9. “Information Sheet: Geometry Factors for Determining the Pitting Resistance and Bending Strength of Spur, Helical, and Herringbone Gear Teeth,” AGMA 908-B89 (R1995), American Gear Manufacturers Association, 1995

Selected References

• C.W. Bowen, Review of Gear Testing Methods, *Gear Manufacture and Performance*, American Society for Metals, 1974, p 137–162

• D.H. Breen, “Physical and Analytical Modeling of Contact Fatigue Pits from Rolling/Sliding Tests,” Technical Paper 87-FTM-8, American Gear Manufacturers Association, 1987

• L. Flamand, D. Berthe, and M. Godet, Simulation of Hertizian Contacts Found in Spur Gears With a High Performance Disk Machine, *Trans. ASME*, Vol 102, Jan, 1981, p 204 doi: 10.1115/1.3254866

• D. Medlin, G. Krauss, D.K. Matlock, K. Burris, and M. Slane, "Comparison of Single Gear Tooth and Cantilever Beam Fatigue Testing of Carburized Steel," Technical Paper 950212, SAE International, 1995 doi: 10.4271/950212

• M.B. Slane, R. Buenneke, C. Dunham, M. Semenek, M. Shea, and J. Tripp, "Gear Single Tooth Bending Fatigue," Technical Paper 821042, SAE International, 1982 doi: 10.4271/821042

• M.N. Webster and C.J.J. Norbart, An Experimental Investigation of Micropitting Using a Roller Disk Machine, *STLE Trib. Trans.*, Vol 38, 1995, p 883 doi: 10.1080/10402009508983485