INTRODUCTION TO

GEAR DESIGN

2nd Edition

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Dedication

One of the things I have enjoyed most about being in the gear industry is the opportunity to learn from some really great people. It isn't possible to list them all here but I'm sure they know who they are. It was their example that lead me to write this book. Whatever good comes from this effort I owe to them.

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Introduction

Albert Einstein once said:

> “Things should be made as simple as possible, but no simpler.”

This book is an attempt to apply that principle to gear design by presenting information from a manufacturing point-of-view rather than a theoretical one. There are no great advances in gear technology described here. The topics discussed are all covered in greater detail in other books, some of which are listed in the “reference” section. The author hopes that this little volume will be of use to the occasional gear designer as a source of handy information and direction to more complete answers to the questions that arise during the design process.

About the 2nd Edition

After finishing this book in 1987 I vowed never to write another gear book. During the years since, however, I came to look at this little volume with a more critical eye and decided it needed just a little updating. What started out as a simple “scan it into the computer and make it look more modern” project grew into a major re-writing effort. I’ve tried to incorporate the lessons learned in 10 years of busy engineering practice at Milwaukee Gear and Pittsburgh Gear. I hope the additional figures and tables will be of value.

Despite the modern convenience of spell check, I’m sure there are a few typos left, and that a 3rd edition will be needed in a few years to correct them.[1]

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[1] Editor’s note: This document is a 2015 revision based on a scan of the 2nd Edition. All content has been preserved, but has been converted to PDF text and vector diagrams, along with new editing, numbering, formatting, typesetting, and internal and external hyperlinks.

Chapter 1

How to Use This Book

Every gear engineer must answer a series of questions before he can complete a design. The information in this book is organized in the usual sequence of these questions:

1. What kind of gears should I use?
2. What should they be made of?
3. What should they look like?
4. How should they be made?
5. How should they be inspected?

Somewhere between questions 1 and 2 the size of the gears must be determined through a rating-calculation procedure. This subject is *not* covered in this book for reasons that will be discussed later. A list of references has been provided to assist you in getting the answer to that question, and any others which this book raises for you.

Chapter 2

What Kind of Gears Should I Use?

Successful gear systems often depend as much on selecting the right gear for the job as on the proper design of the individual parts. Gears can be made in a wide variety of forms, each with its own strengths and weaknesses. In some applications different gear types can be used with equal success. There are other cases where a specific type of gear has become the “standard” due to its unique characteristics. Table 2.1 shows the most common kinds of gears, organized by shaft orientation, showing their relative characteristics compared to other types of the same shaft orientation. Additional comments on each are made in the following paragraphs.

Parallel-Shaft Gears

Spur gears are by far the most common type of parallel-shaft gear. They are simple to design, highly efficient, and relatively forgiving of mounting errors. Spur gears can handle high horsepower and shock loads but are not the most compact way to transmit power due to the relatively low contact ratio that can be obtained. Contact ratio is a measure of smoothness of operation and is related to the number of teeth in contact (and sharing the load) at any one time. Well-designed spur gears should never have a contact ratio of less than 1.2, but it is hard to get a contact ratio much over 1.8 without employing a non-standard “high contact ratio” tooth form, for which special tooling is required. Spur gears do not generate thrust forces (loads in the direction of the shaft axis), which allows for much simpler housing and bearing arrangements.

Helical gears are often thought of as “twisted” spur gears because the teeth run at an angle to the shaft axis. This “helix angle” is produced by setting the cutting tool at an angle to the workpiece and using a differential to vary the relative speed of rotation between the tool and the workpiece. The helix angle raises the contact ratio by bringing more teeth into contact across the face of the gear. This “face” contact ratio is added to the “profile” contact ratio of the spur gear to give a “total” contact ratio that can be tailored to meet higher load requirements and operating speeds. There is a thrust load created by the helix angle that complicates bearing selections, however. Analysis of bearing loads can be complex. Consult your bearing manufacturer or one of the reference books for suggested analysis methods.

Double-helical gears have two “opposite-hand” helical gears on a single shaft. This theoretically creates equal and opposite thrust forces that cancel each other, giving the advantages of helical gears without the bearing-load problems. In practice, however, it can be difficult to insure that each “helix” carries an equal load. External thrust loads caused by coupling miss-alignments or imbalance can interfere with the ability of the gears to “float” axially and find their equilibrium point. This causes one side of the gear to carry more load and wear out sooner. The design of mounting and bearing arrangements for double-helical gears turns out to be just as difficult as for helical gears. These gears can handle very high loads and operating speeds, which accounts for their popularity in pump drives and marine propulsion units. A great deal of research has

Table 2.1: Relative Characteristics of Gear Types

1 = Best 5 = Worst

Type	Ratio Range	Power Capacity	Speed Range	Relative Cost	Space Required	Approx. Efficiency	Mounting Costs
Parallel Shafts							
Spur	1 to 10	4	4	1	4	95 to 98 %	1
Helical	1 to 10	3	2	2	3	95 to 98 %	3
Double-Helical	1 to 10	2	1	4	2	95 to 98 %	2
Internal	2.5 to 12	5	5	3	5	90 to 95 %	4
Planetary	2.5 to 12	1	3	5	1	85 to 95 %	5
Intersecting Shafts							
Straight-Bevel	1 to 8	2	2	1	2	95 to 98 %	1
Spiral-Bevel	1 to 8	1	1	2	1	95 to 98 %	2
Face	3 to 8	3	3	3	3	90 to 95 %	3
Non-Intersecting Shafts							
Worm	3 to 120	1	3	1	1	50 to 90 %	2
Crossed-Helical	1 to 10	5	5	5	5	50 to 95 %	1
Hypoid	2.5 to 10	2	1	3	2	90 to 95 %	2
"Face" Worm	3 to 120	3	2	2	3	50 to 95 %	4
Face	3 to 8	4	4	4	4	90 to 95 %	5

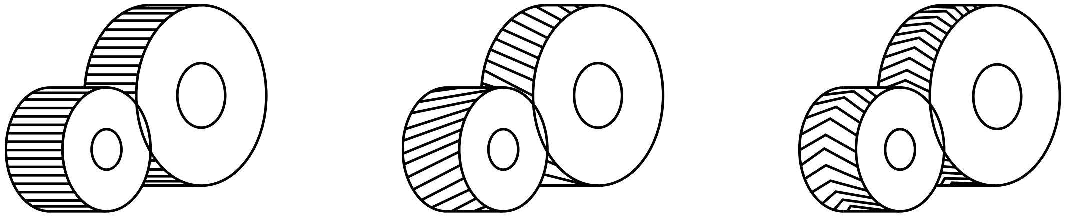
Notes:

1 The ratio ranges shown are the extreme limits. For high-power applications and manufacturing economy the designer is advised to limit spur and helical gearsets to a maximum of 5.5:1. Worms should be 5:1 to 70:1.

2 Internal gearsets over 8:1 are not recommended.

3 Planetary gearsets lower than 4:1 or higher than 7:1 present some unique design problems that the novice designer is advised to avoid.

4 Consult the appropriate AGMA standard or a reference book to satisfy yourself that the proposed design maintains the recommended relationships between various gear parameters such as face-width-to-pitch-diameter.



(a) Spur **(b) Helical** **(c) Double-Helical (With Gap) Herringbone (No Gap)**

(d) Internal **(e) Planetary**

Figure 2.1: Parallel-Shaft Gear Types

been published on the system dynamics of these drives but much of it may be difficult for the non-expert to use.

Internal gears can be made in spur or helical forms. Contact ratios are slightly higher than for external gears of the same proportions, but load-carrying capacity suffers from face-width limitations and an inability to mount adequate bearing on the pinion. The internal gear is also very awkward to mount, which can make the drive difficult to package.

Planetary gears use multiple gear meshes inside an internal gear. These meshes have the effect of canceling the “separating” loads (forces tending to push the gears apart), which reduces the bearing loads. As power capacity is calculated on a “per mesh” basis the planetary-gear design allows for very high loads in a compact space. The “down side” of all this is that lubrication requirements and thermal losses can put limits on the allowable operating speeds unless external cooling and lube systems are employed (which reduces the “compactness” advantage). In addition, a high degree of precision is required in part manufacture to insure that the load is shared equally. There are some specific mathematical relationships that must be maintained in the design of planetary gearsets, which can restrict the ability to obtain exact ratios. The best approach for the novice designer is to read everything mentioned about planetaries in the reference books and to look carefully at existing installations.

Intersecting-Shaft Gears

Bevel gears are the most popular means of connecting intersecting shafts. Straight-bevel gears (including Coniflex) have much in common with spur gears, while spiral-bevel gears (including Zerols) are similar to helical gears in operating characteristics. All bevel gears are extremely sensitive to mounting accuracy, and require careful analysis of bearing loads. The Gleason Works has a lot of information on the design of bevel gears and mountings. The published limitations on proportions and numbers of teeth should be strictly observed. Doing otherwise can lead to unsolvable manufacturing and field problems.

Face gears are not commonly used in power-transmission designs due to their low power capacity and lack of standardized calculation procedures. Face-gear design information is available in some of the reference books listed at the end of this manual. These gears can be useful in some timing and indexing applications. Consult an experienced manufacturer before designing any "new" face gears, as tooling considerations are critical.

Non-Intersecting-Shaft Gears

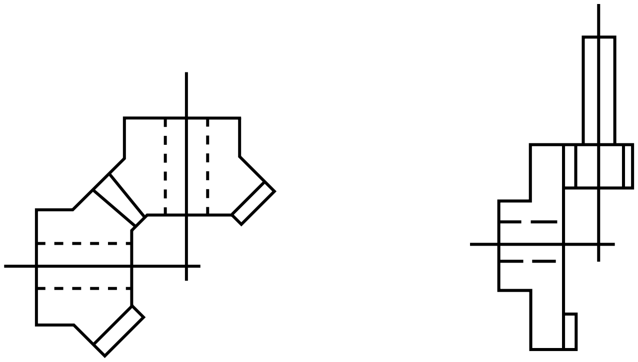
Worm gears were originally designed as "jacks" for raising and lowering weights. They are uniquely suited for static-load applications because of their tendency to "self lock" under certain conditions. "Self locking" occurs when the worm can turn the gear but the gear cannot turn the worm — the load cannot cause the drive to backup. This phenomenon does not occur in all wormgear sets and should not be counted upon to take the place of a brake for safety-related applications. Wormgears can also provide the highest possible reduction ratio in a single "pass" and are just about the only type of gear where the gear-diameter-to-pinion-diameter ratio does not correspond to the reduction ratio. This allows modern power-transmission wormgear boxes to be very compact in comparison to other gearboxes of similar reduction. The large amount of sliding action in worm meshes can result in low efficiency and power limitations due to thermal losses. The meshing action is very smooth, making these gears ideal for indexing applications. Calculation procedures are available through AGMA and in most reference books.

Crossed-helical gears can be thought of as a simple form of "non-enveloping" wormgear. Load capacity is severely limited because of the small contact area between the gear and the pinion. These gears are inexpensive to make and are very forgiving of mounting errors, however, which makes them popular for low-power "takeoffs" or timing purposes (like packaging machines). Calculation procedures are not standardized through AGMA but can be found in some reference books.

Hypoid gears are a modified form of spiral-bevel gear. All comments made about bevel gears apply here as well. Rear-wheel-drive auto and truck axles are the most popular use of Hypoid gears.

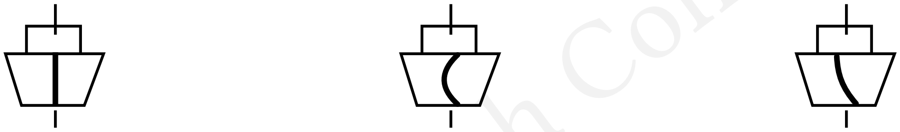
"Face worm" gears have been sold under the trade names "Helicon" and "Spiriod". The original design patents have now expired and there is nothing to prevent a "second source" from developing similar gears. The proprietary nature at these gears has tended to make them more expensive than worms or Hypoids, and less well understood. The design and rating methods that have been published for these gears have not been independently tested or sanctioned by AGMA. It appears these gears share some characteristics with worms and Hypoids, but may have other weaknesses or strengths.

Face gears can also be designed for non-intersecting shafts. The comments previously made about face gears apply here as well.

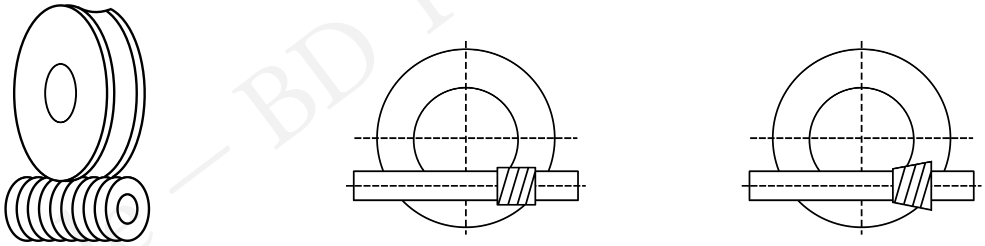


(a) Bevel **(b) Face**

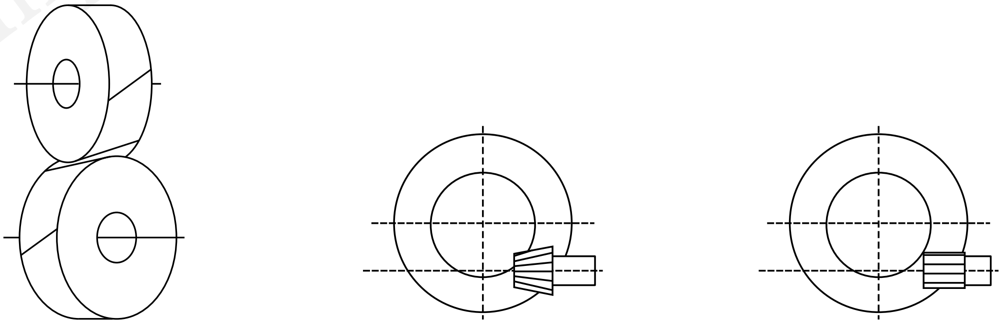
Figure 2.2: Intersecting-Shaft Gear Types



(a) Straight or Coniflex **(b) Zerol** **(c) Spiral**



(d) Worm **(e) Helicon** **(f) Spiroid**



(g) Crossed Helical **(h) Hypoid** **(i) Offset Face**

Figure 2.3: Non-Intersecting-Shaft Gear Types

Chapter 3

What Should They Be Made Of?

Rating Calculations

Gear-rating calculation procedures have been specifically excluded from this manual. The author feels that there is no simple way to cover this subject without compromising the adequacy of the analysis. Anyone designing gears without access to the appropriate AGMA standards and a willingness to spend some time studying them is asking for a lot of trouble. There are a number of packages available for personal computers that claim to perform “complete gear analysis” according to the current AGMA standards. These are great time savers, but their use by inexperienced designers can be dangerous. There are many factors in the rating formulas that must be carefully considered for each application — factors which even the “experts” may disagree on. The best policy is maintain a skeptical attitude in using any rating method, manual or computerized. Believe in what works, not in computer printouts!

Gear Materials and Heat Treatment

While material and heat-treatment selection are an important part of any rating calculation, they also have a major impact on the manufacturing processes required. Table 3.1 lists the relative characteristics of some popular gear materials so that comparisons can be made of the manufacturing difficulties of alternate choices. For general applications it is best to confine material selections to those listed in the table. Lots of other materials (including aluminum, powdered metal, stainless steel, and exotic “tool steel” alloys) have been used to make gears, but their allowable stresses and lubrication requirements have not been standardized. If you choose to use a material not listed, you must be prepared to do some digging to get that information and spend the time and money needed to verify its accuracy.

Through-hardening steels are the most popular gear materials because they can be cut after reaching their final hardness. This eliminates heat-treating distortion that can require expensive finishing operations. The through-hardening steels are listed in order of relative power capacity (lowest to highest), with fully-annealed 1018 steel being used as the “baseline”. Very soft steels are often “gummy” and can be difficult to cut accurately. Cutting steel over 350 BHN can also be a problem.

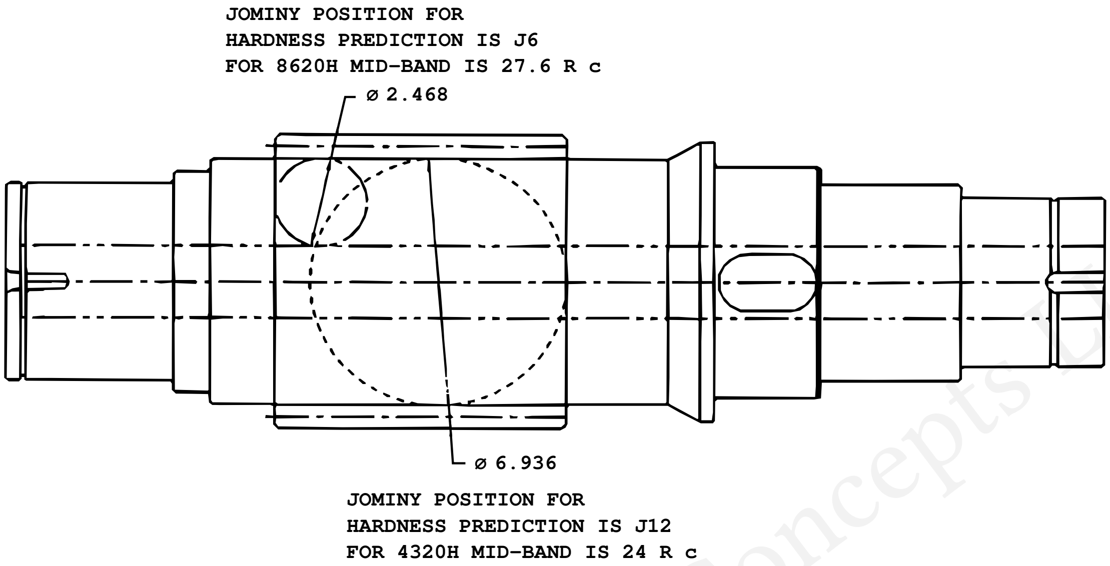
Steel alloys have different “hardening profiles” (the relationship of hardness to distance from the surface) that must be matched to the size of the part and the hardness needed (see Figure 3.1). Generally speaking, the lower the alloy is on the list, the better the hardening profile. It is important that highly-stressed parts have uniform hardness — soft “cores” can lead to field service problems. The author prefers to limit the use of 1045 material to parts requiring less than 240 BHN. Do not use 1045 for parts that will be operated at low temperatures. 4140 works well for parts up to 3 NDP and for critical sections up to about 4″. For coarser pitches and larger critical sections 4340 is preferred rather than 4150. The author does not advocate the use of re-sulphurized steels, as they have an elevated notch sensitivity.

Some alloys, such as 4140 and 4150, can become extremely brittle if hardened over 430 BHN.

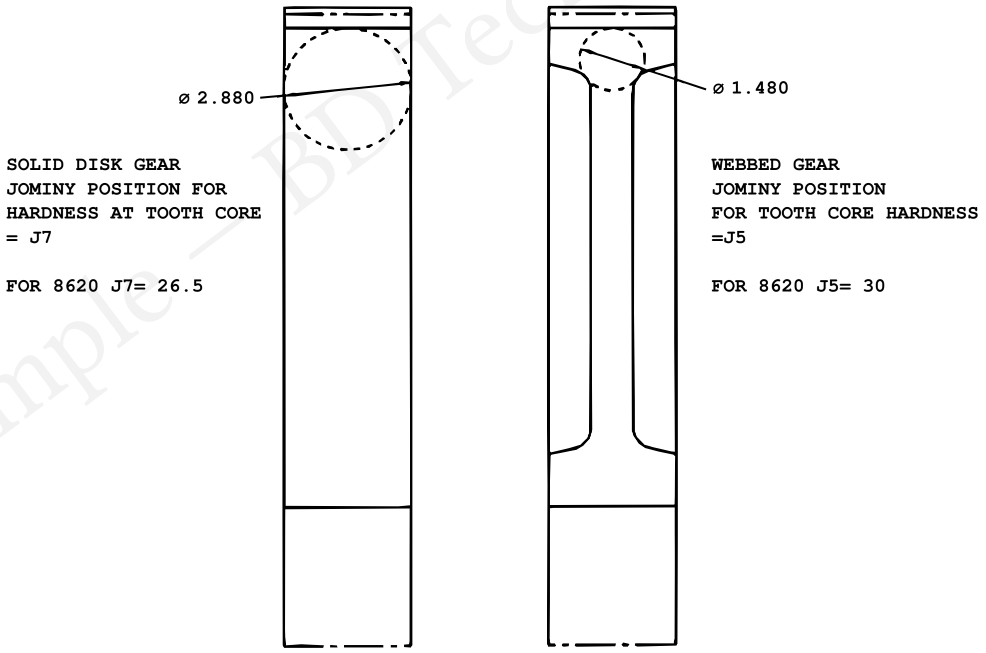
Table 3.1: Popular Gear Materials

Designation	Cost^1	Relative Durability^2	Relative Strength^3	Maximum Hardness	Difficulty of Manufacture	Heat-Treat Distortion
Through-Hardening Steels						
1018	1.00	1.00	1.00	180 BHN	1.10	Not a concern with through-hardened steels. (Severe if flame or induction hardened.)
1117	1.00	1.00	1.00	180 BHN	1.10	
1045	1.05	1.46	1.25	270 BHN	1.00	
1137	1.05	1.46	1.25	270 BHN	1.00	
1141	1.05	1.46	1.25	270 BHN	1.00	
4140	1.10	2.50	1.50	335 BHN	1.20	
4150	1.15	2.80	1.60	360 BHN	1.30	
4340	1.20	3.00	1.60	390 BHN	1.40	
4350	1.25	3.20	1.65	400 BHN	1.50	
Nitriding Steels						
4140	1.50	3.50	1.35	48 HRC	1.25	Minor
4340	1.50	3.40	1.42	48 HRC	1.25	Minor
Nitralloy	1.75	4.20	1.45	64 HRC	1.25	Minor
Carburizing Steels						
4130	1.50	3.50	1.60	50 HRC	2.50	Severe
4620	1.65	4.00	1.85	55 HRC	2.50	Severe
8620	1.35	4.50	1.97	62 HRC	2.50	Severe
4320	1.50	5.60	2.15	62 HRC	2.50	Severe
4820	1.75	5.60	2.25	62 HRC	2.75	Severe
9310	2.00	5.50	2.12	61 HRC	3.00	Severe
Iron						
G4000 Grey	0.80	0.80	0.40	200 BHN	0.85	Not a concern with iron.
Ductile	1.20	81 % of steel	81 % of steel	260 BHN	Same as steel.	
Malleable	1.00	0.95	0.51	240 BHN	1.00	
Bronze						
Sand-Cast	3.00	0.10	0.17	160 BHN	1.00	Not a concern.
Aluminum Bronze	5.00	0.47	0.72	220 BHN	1.10	

Notes:
1 Cost of material and heat treating relative to non-heat-treated 1018 steel.
2 Durability relative to non-heat-treated 1018 steel.
3 Strength relative to non-heat-treated 1018 steel.



(a) Critical Section on Shaft/Pinions



(b) Critical Section on Webbed Gears

Figure 3.1: Critical Sections in Typical Parts

Always check the "notch sensitivity" of any material that is through-hardened above 375 BHN. Any application for use at extreme temperatures (below 0 °F or above 250 °F) requires careful analysis of the material properties under those conditions. This analysis should be done by a competent metallurgist.

While the AGMA standards do not (at the time this is being written) have different allowable stresses for the various carburizing steel grades, there is ample evidence to suggest that all alloys do not perform equally. Figure 3.2 is a graph of the average (or mid-band) hardness potential of the most popular carburizing steels as found in the "Jominy" hardenability test. There is a significant difference in the curves from one alloy to another. This is important because for carburized gears to perform well the tooth-core hardness must be greater than 25 HRC. Figure 3.3 is a graphical representation of a table in the *AGMA 2004 Materials and Heat Treat Manual*. It clearly shows, for example, that the popular 8620 alloy will not result in a tooth-core hardness of 25 HRC when the tooth size is larger than 4.5 NDP. Figure 3.4 is a typical graph of jominy position vs. critical-section size.

The actual hardness results will vary depending upon the exact chemistry of the material, the specifics of the heat-treat process, and the critical section (see Figure 3.1) of the part. Alloy selection and critical-section analysis are a very important part of carburized-gear design. The author does not advise using high-performance alloys in all cases, but suggests 8620 not be used for teeth larger than 4.5 NDP or for parts with critical sections over 3″. For coarser-pitch application 4320 is preferred.

While nitrided gears can't carry as much load as carburized and hardened ones, they offer the advantage of minimal heat-treat distortion. This usually allows them to be used "un-ground", and greatly reduces manufacturing costs. Material selection for nitrided gears is generally made on the basis of the durability rating required. Nitriding produces a very hard, shallow case that can be susceptible to cracking if overloaded. This process is most successful on teeth smaller than 6 DP.

Carburized, hardened, and ground gears are the ultimate in power capacity. Gear grinding is usually required to correct for heat-treat distortion. Attempts at predicting distortion levels and controlling it during the heat-treating process generally have been unsuccessful. Without grinding it is difficult to maintain AGMA Q-10 tolerance levels. Selective hardening is specified to keep some areas of the part "soft", and this can be done through the use of copper plating or carburizing, machining the case off the desired surfaces, and hardening. Special "stop-off" paints have also been used with great success. Material selections are made on the basis of the durability rating and the case depth required. The AGMA standards and some of the reference books can provide guidance in those areas.

Cast iron is used in many industrial and automotive gear applications because of low material cost. Casting methods have been developed that can produce the required core hardness right from the mold, saving an expensive heat-treat operation. (If not done properly, however, the parts become as hard as tool steel and unusable due to brittleness.) These materials are getting better every year as a result of the research money being spent on them. Some experts feel these new iron formulations can carry the same loads as through-hardened gears of the same core hardness. For high-volume uses the cost savings may make these materials very attractive to those willing to verify the lab results.

Bronze is the material of choice for most wormgears, but is seldom used on other gear types unless the power requirement is low. Some bronze alloys can be heat treated to improve their capacity. Casting methods can greatly affect the material properties, and the gear designer must make sure the drawing specifies the method desired.

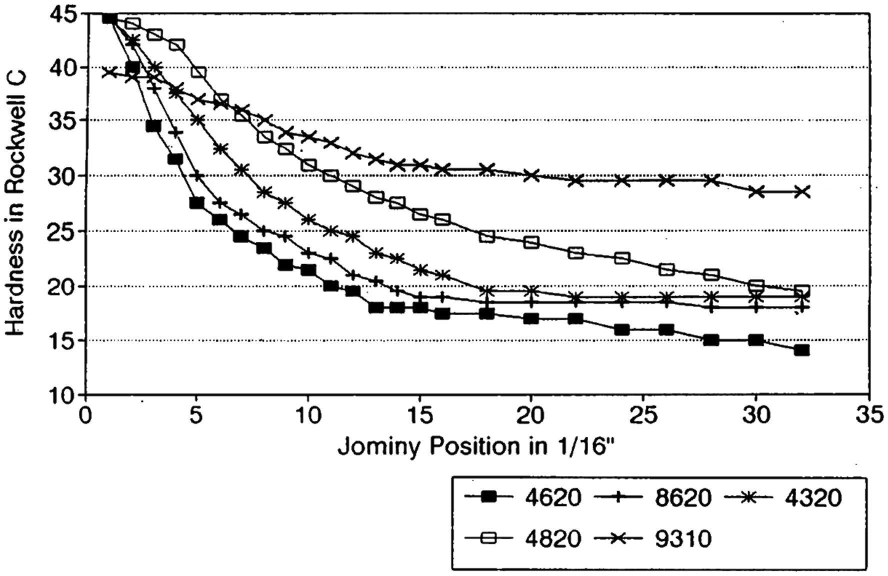


Figure 3.2: Mid-Band Jominy Hardness vs. Alloy

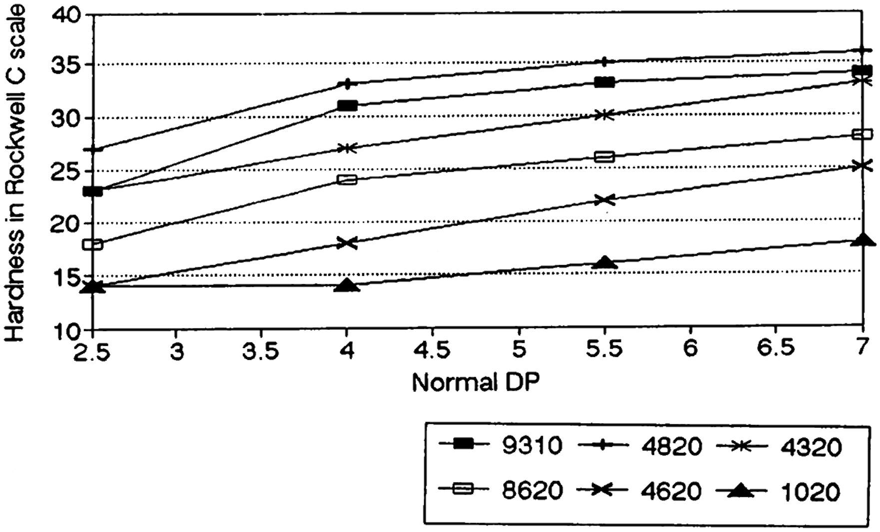


Figure 3.3: Approximate Min. Core Hardness vs. Alloy (per ANSI/AGMA 2004 Table 5-3)

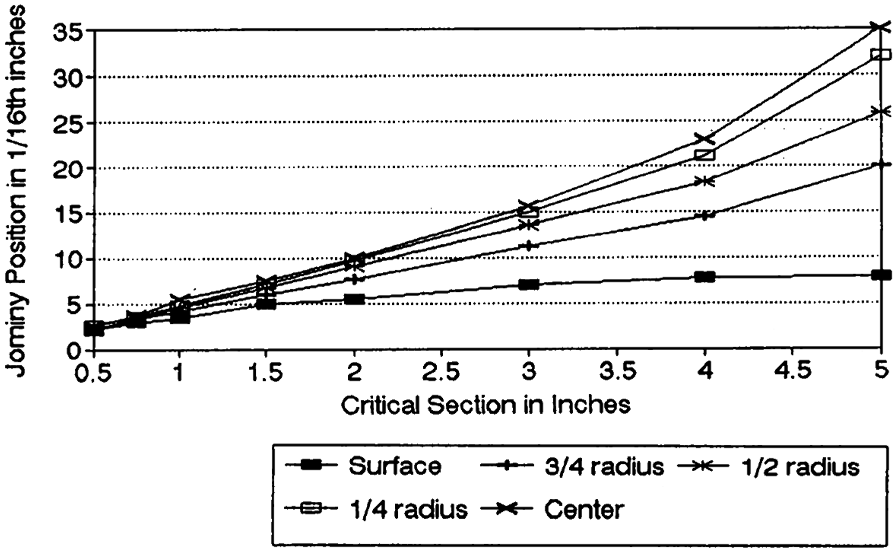
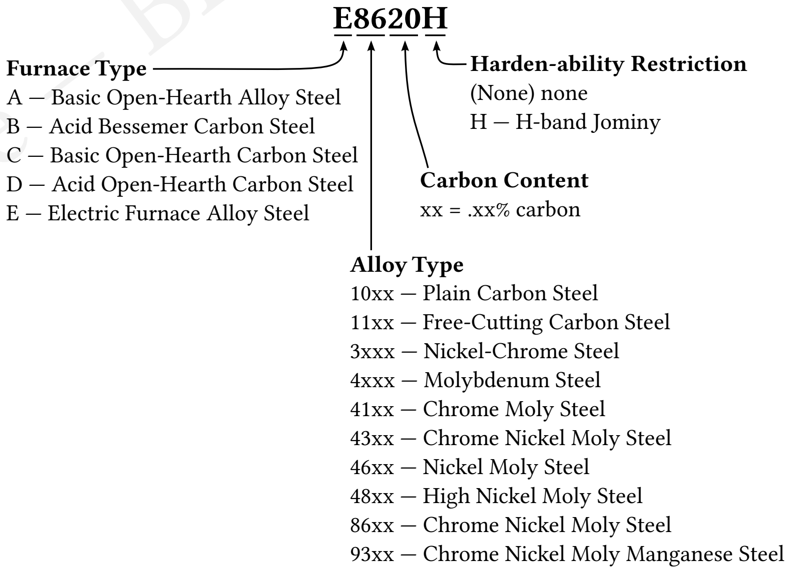


Figure 3.4: Jominy Position vs. Critical Section (for oil quench with good agitation)



Furnace Type
A — Basic Open-Hearth Alloy Steel
B — Acid Bessemer Carbon Steel
C — Basic Open-Hearth Carbon Steel
D — Acid Open-Hearth Carbon Steel
E — Electric Furnace Alloy Steel

Harden-ability Restriction
(None) none
H — H-band Jominy

Carbon Content
xx = .xx% carbon

Alloy Type
10xx — Plain Carbon Steel
11xx — Free-Cutting Carbon Steel
3xxx — Nickel-Chrome Steel
4xxx — Molybdenum Steel
41xx — Chrome Moly Steel
43xx — Chrome Nickel Moly Steel
46xx — Nickel Moly Steel
48xx — High Nickel Moly Steel
86xx — Chrome Nickel Moly Steel
93xx — Chrome Nickel Moly Manganese Steel

Figure 3.5: AISI Numbering System for Steel

Table 3.2: Approximate Minimum Hardenability of 1045, 4140, 4150, & 4340

Jominy Position	Brinell Scale			
	1045	4140	4150	4340
1	555	525	630	525
2	390	525	630	525
3	295	514	630	525
4	270	495	620	525
5	260	495	615	525
6	250	480	595	525
7	250	455	595	525
8	245	444	575	514
9	240	410	575	514
10	235	390	555	514
11	230	370	540	495
12	220	360	525	495
13		355	495	480
14		345	480	465
15		335	455	465
16		330	444	455
18		320	420	444
20		310	400	430
22		310	380	420
24		300	370	410
26		300	360	400
28		295	350	390
30		295	350	380
32		285	350	370

The Gear-Design Process

1. Determine Loads and Speeds
    - Prime-mover nameplate power and speed
    - Duty cycle
    - Reliability
    - Smoothness of operation
    - External loads
    - Experience with similar applications
2. Determine Gear Type
    - Physical arrangement
    - Efficiency
    - Bearing considerations
    - Noise and vibration
    - Experience with similar applications
3. Determine Material and Heat Treatment
    - Strength vs. wear requirements
    - Lubrication issues
    - Space limitations
    - Process limitations
    - Cost issues
    - Delivery issues
4. Determine Quality Needed
    - Operating speed
    - Noise and vibration
    - Reliability and failure mode issues
5. Basic Gear Design
    - Space available
    - Standardized tooling
    - Process capabilities
6. Detail Design
    - Stress analysis
    - Raw material form
    - Assembly issues
    - Design for manufacturing
    - Cost review

Chapter 4

What Should They Look Like?

Mounting Characteristics

No matter how much care is taken in the design and manufacture of gears, they are sure to fail if improperly assembled or inadequately mounted. Many "gear" problems are caused by lack of attention to the accuracy required in machining the housing, in assembling the gears and bearings to the shafts, and in aligning the sub-assemblies. The author knows of gearboxes that, after giving 30 years of excellent service, have failed within hours of "field" rebuilding by inexperienced mechanics. If you are not sure how to handle a particular aspect of a design or maintenance project, ask for help or check the reference books listed in this manual. Most bearing manufacturers will be happy to review your drawings and bearing selections at little or no charge. If your gear supplier has an engineering department, they may also be available to "consult" on your design project or to train your maintenance and assembly people in proper methods of handling and adjusting gears.

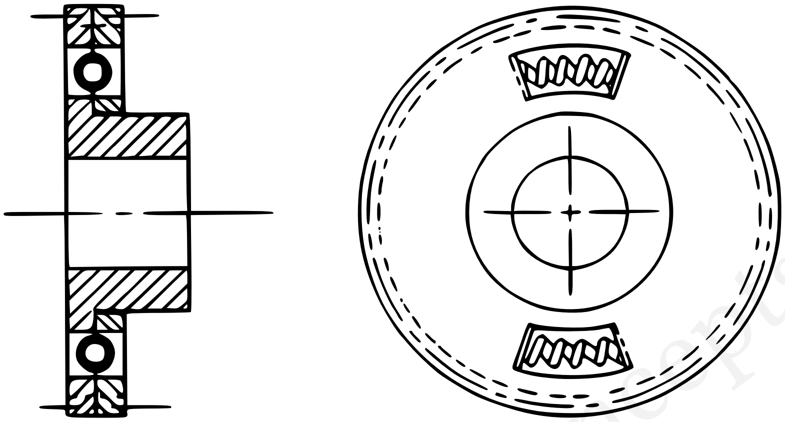
Backlash

Backlash is one of the most misunderstood concepts in gearing. An individual gear cannot have backlash — it can only have a tooth thickness. Backlash occurs when gears are mated together on a given center distance and the sum of their tooth thicknesses is less than their circular pitch. The backlash of a pair of gears will vary at some points in the rotational cycle due to run-out and cutting inaccuracies. If the center distance is increased the backlash will increase; if it is reduced the backlash will decrease. Don't confuse "low backlash" with "high quality". Except for applications that require positioning accuracy, such as index tables or radar drives, or that are subject to frequent reversing loads, "too much" backlash seldom effects gear performance. Not having enough backlash can result in the gears "binding" under some conditions, especially at low temperatures when steel gears are used in an aluminum housing. Gears that bind are certain to fail.

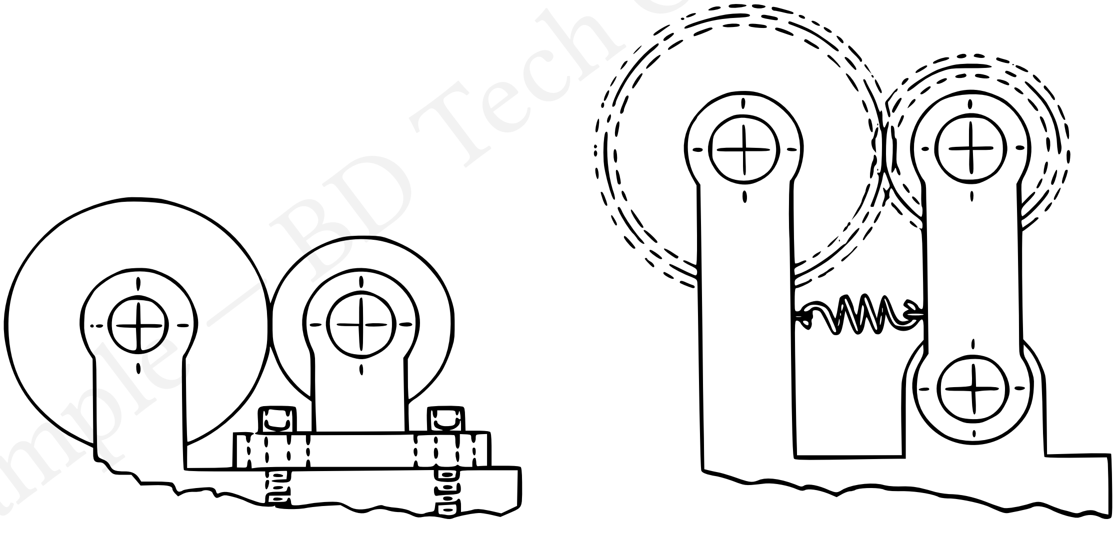
When low backlash is required, the best approach is to use "anti-backlash" gears or adjustable centers (see Figure 4.1). Tight tolerances on tooth thicknesses and center distances are seldom effective and can be very expensive. Anti-backlash gears consist of two gear halves that are spring loaded to adjust the "effective" tooth thickness to fill in the space available on the mating part. These gears are not used to transmit significant amounts of power, as the required spring pressures become hard to obtain in the space available. Adjustable centers can handle slightly higher loads but are expensive to manufacture. The reference books discuss "backlash" extensively and some manufacturers include a limited range of anti-backlash gears for instrument use in their catalogs.

Blank Tolerancing

The difference between a "good" gear and a "bad" one can often be traced to how accurately the blank was machined. In a production run of gears, for example, those having bores close to the low limit (or maximum material condition) will fit the cutting arbor more snugly and usually exhibit the least "run-out". If gears are to be cut in a "stack" the perpendicularly of the blank sides to the bore



(a) "Scissors Gear"



(b) Adjustable Centers

(c) Spring-Loaded Centers

(Illustrations extracted from
AGMA Design Manual for Fine Pitch Gearing [AGMA 370.01].
Used by permission of AGMA.)

Figure 4.1: Anti-Backlash Methods

will similarly influence the results. It is important to "match" the tolerancing of those part features — which will be used for work-locating during the machining process — to the accuracy needed in the final part. Your gear supplier may have some specific requirements in this area, but the values shown in Tables 4.1 to 4.3 are a good place to start.

Quality Classes

Selecting the proper quality class for a particular application is one of the most controversial areas of gear design. AGMA has provided a chart in AGMA 2000 (formerly AGMA 390.03) that can be used to select the quality level needed. Many of the texts listed in the reference section of this guide have additional information on this topic. Quality level should be a function of application, power level, and operating speed. Table 4.4 is the author's suggestion for minimum quality level vs. maximum pinion pitch-line velocity when relatively smooth applications are considered.

It is very important to remember that increased quality levels cost money. If you want cost-effective designs you must resist the urge to "solve" your gear problems by over-specifying quality levels. Even the "best" gears will fail if they are not mounted accurately, or properly sized for the load and system dynamics. Table 4.5 shows the quality levels normally achievable for various gear elements by modern manufacturing techniques. The column on "relative cost" reflects not only the additional time and effort needed to make the gear teeth, but also the extra expense of increased blank accuracy.

Surface Finish

The surface finish of gear teeth is another controversial aspect of gear design. One common misconception is that specifying an AGMA quality class also specifies a tooth-surface finish. AGMA 2000 *does not* include surface finish in its tolerancing. Table 4.6 shows the surface finishes normally produced by common production methods. Comparing this table with the one on quality vs. production method (Table 4.5) shows that there is an indirect relationship between "quality" and "surface finish".

When you specify a tooth surface finish (Table 4.7) you are often requiring costly gear-finishing processes (Table 4.8) that do not increase "quality" as defined by AGMA 2000. It is important to satisfy yourself, by studying whatever information is available (or through field testing), that you need a particular finish to meet your performance objectives. Surface finish has an effect on lubricant film-thickness requirements. While no consensus "standard" has been published on what lubricant viscosities are needed with what surface finishes, it is clear that heavier oil is needed when coarser finishes are present. The use of the heavier lube may or may not be possible in some applications due to cold-starting conditions, thermal considerations, or other issues.

Blank Design

One thing that all gear experts agree on is that you can't make a good gear from a bad blank. "Bad" doesn't just mean poor workmanship: it also refers to poor design or poor tolerancing. A good way to prevent these problems is to become familiar with the processes used to make gears and make provisions in the design of the part to use those processes to your advantage. Once you understand the manufacturing techniques you'll be able to determine which parts of your gear system are likely to be problems while there is still time to make design changes. This is a good time to remember the old adage "If it looks right it probably is." Many gear problems are really "proportion" problems. Long spindly shafts, large gears with small rim or web thicknesses, inadequate housing supports, and poor "packaging" have caused more "gear failures" than anyone

Table 4.1: Typical Gear-Blank Tolerances

(Courtesy of QUAKER CITY GEAR WORKS)

AGMA	Q6	Q7	Q8	Q9 & Q10	Q11 & up
Diameter of Bore	.002	.001	.0007	.0005	.0002
Taper of Bore (No portion to exceed tolerance)	.001/in of length Max .002	.0007/in of length Max .001	.0005/in of length Max .0007	.0003/in of length Max .0005	.0002
Concavity of Mounting & Register Surfaces	.001/in of radius for rigid blanks .0005/in of radius for flexible blanks Total .003			.0005/in of radius for rigid blanks .0003/in of radius for flexible blanks Total .0015	
Convexity of Mounting & Register Surfaces	None for any class				
Lateral Runout of Bevel & Face Gears	.001/in of radius Max .002	.0008/in of radius Max .0016	.0005/in of radius Max .001	.0004/in of radius Max .0008	.0003/in of radius Max .0005
Lateral Runout of Spur & Helical Gears	.002/in of radius Max .004	.0015/in of radius Max .0025	.001/in of radius Max .002	.0007/in of radius Max .0015	.0005/in of radius Max.001
Non-Parallelism	.002/in of radius Max .004	.0015/in of radius Max .0025	.001/in of radius Max .002	.0007/in of radius Max .0015	.0005/in of radius Max.001

Table 4.2: Outside-Diameter Tolerances

(Courtesy of QUAKER CITY GEAR WORKS)

(a) Runout of Outside Diameter with Bore or Centers

Diametral Pitch	AGMA Q5 TO Q8	AGMA Q9 & up
1 – 4	0.015	0.009
5 – 8	0.010	0.006
9 – 13	0.006	0.004
14 – 19	0.004	0.003
20 – 39	0.003	0.002
40 – 79	0.002	0.0015
80 & finer	0.001	0.001

(b) Tolerance of Outside Diameters

D.P.	+0	D.P.	+0
3	−0.020	40	−0.005
5	−0.015	48	−0.004
8	−0.010	64	−0.003
10	−0.008	72	−0.003
12	−0.007	80	−0.002
14	−0.007	96	−0.002
18	−0.007	120	−0.002
20	−0.007	124 & up	−0.001
32	−0.006		

cares to count. Take a careful look at the general “appearance” of your design before making the final drawings.

Tooth-Form Selection

One of the first steps in designing a gear is the selection of the tooth form to be used. To a certain extent this decision is based upon rating requirements, but the choice made will also effect the manufacturing processes used. Table 4.9 shows the “popular” tooth forms in use today. There are many other forms available, and each has its proponents. The author urges caution on the part of anyone who is thinking of using a tooth form not on Table 4.9, as the availability of cutting tools will be limited. The actual variation in tooth strength from one form to another is slight. For critical applications tooth form might make the difference between success and failure, but those instances are rare, and should be left to the “real experts.” Unless very low numbers of pinion teeth are involved, the author sees little need to use anything other than 20 full-depth teeth on new designs. If low numbers of pinion teeth (< 20) are needed, 25 full-depth is the best choice. When making modifications to existing designs, you may have to work with the other forms shown on Table 4.9, but they should be considered “obsolete” for new designs.

Table 4.3: Gear-Blank Standards

(Courtesy of QUAKER CITY GEAR WORKS)

Outside Diameter Tolerances:

Straight-Bevel Gears — All Classes

D.P.	Tol. ±.000
20 – 30	−0.005
31 – 40	−0.004
41 – 56	−0.003
57 – 94	−0.002
95 & finer	−0.001

Back-to-Corner Tolerances:

Bevel Gears

D.P.	Tol. ±.000
20 – 46	−0.002
47 & finer	−0.001

Back-Angle Tolerances — Bevel Gears: ±1°

Surface Finishes — All Types and Classes:

Machine Finish: max. 125 Micro

Grind Finishes by Tolerances:

0.0000 – 0.0002	8 Micro
0.0002 – 0.0005	16 Micro
0.0005 – 0.0010	32 Micro

Threads: All units to be chamfered for:

14½° P.A.	15°
20° P.A.	20°
60° P.A.	30°

Radii: Sharp corners to be broken to 0.005 – 0.015″ radius.

Decimals:

0 – 6″	±.005
6 – 12″	±.010

Angular: ±½°

Thread Tolerances: Class 2 fit

Flatness: Mill Standard

Concentricity of Bearing Journals:

Concentricity of bearing journals, in respect to true center of part, shall be held within the total tolerance of bearing journal diameter size.

Examples:

- Bearing diameter size .125 ± .0003
- Concentricity to true centerline .0003 T.I.R.
- Bearing diameter size .500 ± .0005
- Concentricity to true centerline .0005 T.I.R.

Table 4.4: Minimum Suggested Quality Level vs. Pitch-Line Velocity

For uni-directional service and relatively smooth power flow: $\left(\frac{\text{Peak Load}}{\text{Nominal Load}} \leq 1.25\right)$
(If these conditions are not present, a higher quality level may be needed.)

Maximum PLV in ft/min	Minimum-Suggested AGMA Quality Level
250	6
500	7
1500	8
2500	9
3500	10
5000	11
7500	12
10000	13

PLV in ft/min = pitch diameter × .262 × revolutions per minute

Table 4.5: Achievable AGMA 2000 Quality Levels by Manufacturing Method

Manufacturing Method	Run-out	Involute Profile	Lead	Spacing (Pitch)	Relative Cost
Hobbing (Class B Hob)	8 to 10	8 to 9	8 to 9	8 to 9	1.0 to 1.25
Hobbing (Class A Hob)	9 to 11	8 to 9	9 to 11	8 to 10	1.25 to 1.5
Hobbing (Class AA Hob)	9 to 12	8 to 11	9 to 11	9 to 11	1.5 to 1.75
Shaping (Commercial Cutter)	8 to 10	8 to 10	8 to 11	8 to 10	1.25 to 1.5
Shaping (Precision Cutter)	9 to 11	9 to 10	9 to 11	9 to 11	1.5 to 1.75
Shaving	10 to 12	8 to 10	8 to 12	8 to 12	2.0 to 2.5
Grinding	9 to 14	9 to 14	8 to 14	9 to 14	3.0 to 4.0

Notes:

1 Lower quality levels are generally achievable under most conditions.

2 Upper quality levels require special controls on blanks, tooling, and machinery. This can increase costs significantly.

3 Relative costs compared to Class B hobbing for operations needed to finish gear teeth only. Material and heat-treat costs are not included in this comparison.

4 If heat treating is done after tooth finishing, quality level can drop by two levels or more.

Table 4.6: Achievable Tooth-Surface Finishes by Manufacturing Method

Tooth Size	Effort Required	Hobbing	Shaping	Shaving	Grinding
1 to 3 DP	Normal	125	80 to 125	63	32
	Extra	80	80	32	16
3 to 10 DP	Normal	80	63 to 80	63	32
	Extra	63	63	32	16
10 to 24 DP	Normal	80	63 to 80	50 to 32	32
	Extra	63	63	16	16
24 to 40 DP	Normal	80	63	50 to 32	32
	Extra	63	63 to 32	16	16
40 DP and up	Normal	80	63	not practical	32
	Extra	63	63 to 32		16

Notes:

1 Normal effort involves typical production feeds and speeds.

2 Extra effort involves special controls and procedures on tools and machines. Cycle time may increase significantly.

3 Finishes shown are for through-hardened steel of 230 – 310 BHN.

4 Finish may be poorer on steel below 230 BHN or above 310 BHN.

5 Surface finish may be slightly better in brass, bronze, aluminum, or stainless steel, provided proper feeds and speeds are selected.

6 Surface finish for surface-hardened gears that are not finished after heat treating may be slightly worse due to scale-removal operations.

Table 4.7: Surface-Finish Description

Symbol	Description
${}^{1{,}000}\surd$	Indicates that the surface is very rough and uneven within the dimensional requirements.
${}^{500}\surd$	Indicates that the surface is rough and uneven within the dimensional requirements.
${}^{250}\surd$	Indicates that the surface must be smooth and even to a degree obtainable by tools removing large chips or shavings. Machining marks and grooves discernible to the eye and to touch are permitted, if the surface meets dimensional requirements.
${}^{125}\surd$	Indicates that the surface must be smooth and even to a degree obtainable by tools removing medium chips or shavings. Machining marks and grooves discernible to the eye are permitted, if the surface meets dimensional requirements.
${}^{63}\surd$	Indicates that the surface must be smooth and even to a degree obtainable by tools removing small chips. Machining marks and grooves discernible to the eye are permitted, if the surface meets the dimensional requirements.
${}^{32}\surd$	Indicates the surface must be smooth and even to a degree obtainable by tools removing small particles. Machining marks such as grooves must not be discernible to the eye or touch, if the surface meets the dimensional requirements.
${}^{16}\surd$	Indicates that the surface must be very smooth and even to a degree obtainable by tools removing very small particles. Machining marks such as grooves must not be discernible to the eye or touch, if the surface meets the dimensional requirements.
${}^{8}\surd$	Indicates that the surface must be even to a degree obtainable by tools removing minute particles, generally by grinding. Machining marks such as the fine patterns resulting from grinding must not be discernible to the eye or touch and the surface must have a polished appearance and meet dimensional requirements.
${}^{4}\surd$	Indicates that the surface must be even to a degree obtainable by tools removing very minute particles, generally by honing, lapping, or super-finishing. Machining marks such as very fine patterns must not be discernible to the eye or touch and the surface must have a highly polished appearance and meet dimensional requirements.

ref: *Gear Handbook* by Dudley, Table 9-16

Table 4.8: Surface Finish vs. Tolerance

Symbol	Quality class	Description	Max. RMS value, micro in.	Suitable range of total tolerance	Typical fabrication methods	Approx. relative cost to produce
$\sqrt[1,000]{\ }$	Extremely rough	Extremely crude surface produced by rapid removal of stock to nominal dimension	1,000	0.063 – 0.125	Rough sand casting, flame cutting	1
$\sqrt[500]{\ }$	Very rough	Very rough surface unsuitable for mating surfaces	500	0.015 – 0.063	Sand casting, contour sawing	2
$\sqrt[250]{\ }$	Rough	Heavy toolmarks	250	0.010 – 0.015	Very good sand casting, saw cutting, very rough machining	3
$\sqrt[125]{\ }$	Fine	Machined appearance with consistent toolmarks	125	0.005 – 0.010	Average machining — turning, milling, drilling; rough hobbing and shaping; die casting, stamping, extruding	4
$\sqrt[63]{\ }$	Fine	Semi-smooth without objectionable tool marks	63	0.002 – 0.005	Quality machining — turning, milling, reaming; hobbing, shaping; sintering, stamping, extruding, rolling	6
$\sqrt[32]{\ }$	Smooth	Smooth, where toolmarks are barely discernible	32	0.0005 – 0.002	Careful machining; quality hobbing and shaping; shaving; grinding; sintering	10
$\sqrt[16]{\ }$	Ground	Highly smooth finish	16	0.0002 – 0.0005	Very best hobbing and shaping; shaving; grinding, burnishing	15
$\sqrt[8]{\ }$	Polish	Semi-mirror-like finish without any discernible scratches or marks	8	0.0001 – 0.0002	Grinding, shaving, burnishing, lapping	20
$\sqrt[4]{\ }$	Super-finish	Mirror-like surface without tool grinding or scratch marks of any kind	4	0.00004 – 0.0001	Grinding, lapping, and polishing	25

ref: *Gear Handbook* by Dudley, Table 9-17

Table 4.9: Popular Tooth Forms

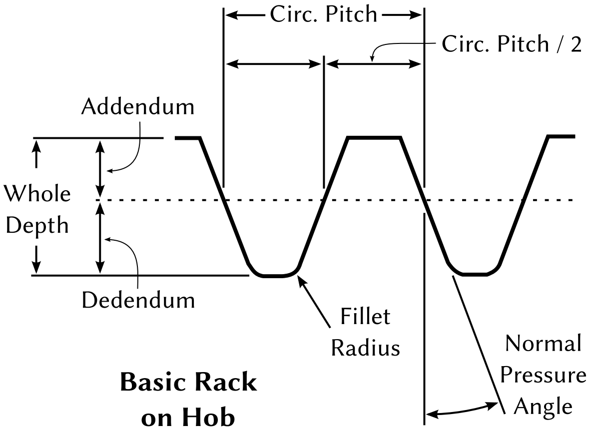
Dimensions shown are for 1 NDP.
For other sizes, divide dimensions shown by NDP needed.

Tooth Form	Normal Pressure Angle	Whole Depth	Addendum	Dedendum	Fillet Radius	Circular Pitch
Full Depth	14.5°	2.157	1.00	1.157	0.21	3.1416
Full Depth	20°	2.157	1.00	1.157	varies	3.1416
Full Fillet	20°	2.250	1.00	1.250	0.30	3.1416
Pre-Shave or Pre-Grind	20°	2.350	1.00	1.350	0.30	3.1416
Stub	20°	1.800	0.80	1.000	0.20	3.1416
Full Depth	25°	2.250	1.00	1.250	0.25	3.1416
Full Fillet	25°	2.300	1.00	1.300	0.30	3.1416
Fellows Stub (x/y)	20°	2.25/y	1.00/y	1.25/y	varies	3.1416/x
Nutall	20°	1.728	0.79	.943	varies	3.1416

Notes:

1 Fellows stub is also called “combination pitch.”

2 Nutall system should not be used for new designs.



Chapter 5

How Should They Be Made?

Gears can be made by a number of machining and “near-net shape” processes. The “near-net shape” processes (plastic molding, powder-metal forging, and stamping) require large “upfront” investments in tooling, and are usually restricted to very high volume (5000+ pieces) applications. It is very expensive to make changes to these tools, so it is advisable to make prototypes by less expensive methods, usually machining them from the same material as planned for the final product. Each “near net” process has its own unique requirements, and it is best to work closely with a couple of suppliers to make certain the part design is compatible with the process desired. The power capacity of plastic and powdered metal gears is not well “standardized”, and a thorough testing program is suggested for all new applications.

The machining methods used to make gear teeth can be divided into a number of subcategories, each of which must be well understood if the gear designer is to avoid manufacturing problems and high production costs. Careful selection of tooth size (Diametral Pitch or Module), for example, can avoid the need for special hobs and shave 8 to 12 weeks off the required lead time. Asking for a ground tooth when there is only clearance for a 3-inch diameter cutter might triple the cost of the part, double the lead time, and restrict you to a couple of suppliers. The following paragraphs will provide some insight into the most common machining methods, and help you select the best process for your gears.

Milling

Milling gear teeth with a cutter having the same profile as the tooth space is the oldest method still in current use. Milling is most commonly used to produce special course-pitch (less than 1 DP) gears or unusual non-involute forms that are difficult to generate with a hob. Milling cutters are available to cut a “range” of tooth numbers (see Table 5.1). If more accuracy is required, special cutters with the form of an exact tooth number can be made. Modern cutter manufacturing techniques can produce excellent results, but it is difficult to produce much better than an AGMA Class 7 gear by this method. It is advisable to make both mating parts of a gearset by milling to avoid meshing problems related to profile errors. Most of the machines used to mill gear teeth are unable to provide “double plunge” cutting cycles, so it is important to allow plenty of cutter clearance on one end of the part. Special small-diameter cutters can be made, but there are limitations, so make sure to consult your gear supplier or a tool manufacturer.

Hobbing

Hobbing is the most popular gear-manufacturing method, combining high accuracy with high production speed. A wide variety of cutting tools are available “off the shelf” (see Tables 5.2 and 5.3) in quality levels to match part-quality requirements, making it easy to get the tooth form you need without having to wait for or pay for custom

Table 5.1: Normally-Available Milling Cutters

Offered in 14.5° and 20° NPA.

NDP	Normal Cutter Diameter	Minimum Cutter Diameter
1	8.5	8.5
1.25	7.75	7.75
1.5	7	7
1.75	6.5	6.5
2	5.75	5.75
2.25	5.75	5.75
2.5	5.75	5.75
2.75	4.75	4.75
3	4.75	4.75
3.5	4.5	4.5
4	4.25	3.5
4.5	3.5	3.5
5	3.75	3.375
6	3.5	3.125
7	2.875	2.875
8	3.25	2.875
9	2.75	2.75
10	2.75	2.375
12	2.625	2.25
14	2.5	2.125
16	2.375	2.125
18	2.375	2
20	2.375	2
24	2.25	1.75
28	2.25	1.75
32	2.25	1.75
36	2.25	1.75
40	1.75	1.75
48	1.75	1.75
56	1.75	1.75
64	1.75	1.75

Cutter Number	Minimum Number of Teeth	Maximum Number of Teeth
1	135	Rack
2	55	134
3	35	54
4	26	34
5	21	25
6	17	20
7	14	16
8	12	13

Note: Teeth smaller than 3.5 NDP are seldom milled.

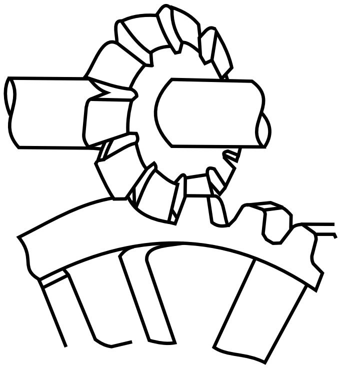


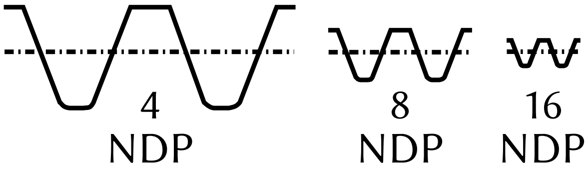
Image courtesy of ASH GEAR & SUPPLY

Table 5.2: Normally-Available Gear Hobs

(a) Diametral-Pitch Hobs

Offered in 14.5°, 20°, and 25° NPA.

NDP	Module	Normal Diameter	Minimum Diameter
1	25.4	10.75	10.75
1.25	20.32	8.75	8.75
1.5	16.9333	8	8
1.75	14.5143	7.25	7.25
2	12.7	5.75	5.75
2.25	11.2889	5.5	5.5
2.5	10.16	5	5
2.75	9.2364	5	5
3	8.467	4.5	4.5
3.5	7.257	4.25	4.25
4	6.35	4	4
4.5	5.644	4	4
5	5.08	3.5	3.5
6	4.233	3.5	3.5
7	3.6286	3.25	3.25
8	3.175	3	2
9	2.822	3	2
10	2.54	3	1.875
12	2.1167	2.75	1.875
14	1.8143	2.5	1.875
16	1.5875	2.5	1.875
18	1.4111	2.5	1.25
20	1.27	2.5	1.25
24	1.0583	2.5	0.9375
28	0.9071	2.5	0.9375
32	0.7938	2.5	0.9375
36	0.7056	2.5	0.75
40	0.635	2.5	0.75
48	0.5292	2.5	0.75
56	0.4536	1.875	0.75
64	0.3969	1.625	0.75
72	0.3528	1.625	0.75
80	0.3175	1.625	0.75
96	0.2646	1.5	0.75



(b) Module (Metric) Hobs

Offered in 20° NPA.

Module	NDP	Normal Diameter	Minimum Diameter
0.2	127	1.25	0.9375
0.3	84.6667	1.625	0.9375
0.4	63.5	1.875	0.9375
0.5	50.8	1.875	0.875
0.6	42.3333	1.875	0.875
0.7	36.2857	1.875	0.875
0.75	33.8667	2.5	1.125
0.8	31.75	1.875	1.25
0.9	28.2222	1.875	1.25
1	25.4	2.5	1.25
1.25	20.32	2.5	1.875
1.5	16.9333	2.5	1.875
1.75	14.5143	2.5	1.875
2	12.7	2.75	1.875
2.25	11.2889	2.75	1.875
2.5	10.16	2.75	1.875
2.75	9.2364	3	2
3	8.4667	3	2
3.25	7.8154	3	3
3.5	7.2571	3	3
3.75	6.7733	3	3
4	6.35	3.5	3.5
4.25	5.9765	3.25	3.25
4.5	5.6444	3.5	3.5
4.75	5.3474	3.5	3.5
5	5.08	3.5	3.5
5.5	4.6182	3.5	3.5
6	4.2383	4	4
6.5	3.9077	4	4
7	3.5286	4.25	4.25
8	3.175	4.5	4.5
9	2.8222	5	5
10	2.54	5	5
11	2.3091	5.5	5.5
12	2.1167	5.75	5.75
14	1.8143	6.5	6.5
15	1.6933	6.5	6.5
16	1.5875	8	8
18	1.4111	8.25	8.25
20	1.27	8.75	8.75
22	1.1545	9.5	9.5
24	1.0583	10.75	10.75
25	1.016	10.75	10.75
27	0.941	10.75	10.75

Table 5.3: Normally-Available Spline Hobs

(a) Diametral-Pitch Hobs

Offered in 30° NPA.

NDP	Normal Diameter	Minimum Diameter
2.5/5	4	4
3/6	4	4
4/8	3.5	3.5
5/10	3	3
6/12	3	3
8/16	2.75	1.875
10/20	2.5	0.875
12/24	2.5	0.875
16/32	2.5	0.875
20/30	2.5	0.875
20/40	2.5	0.875
24/48	2.5	0.75
32/64	2.5	0.75
40/80	2.5	0.75
48/96	2.5	0.625

(b) Diametral-Pitch Hobs

Offered in 37.5° and 45° NPA.

NDP	Normal Diameter	Minimum Diameter	
6/12	3	3	
8/16	2.75	2.75	
10/20	1.875	1.25	
12/24	1.875	1.25	
16/32	2.5	1.25	
20/40	2.5	1.25	
24/48	1.875	1.25	
32/64	1.875	1.125	
40/80	1.875	1.125	
48/96	1.875	1.125	
64/128	1.875	1.125	45° only
80/160	1.875	1.125	45° only

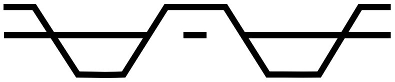
(c) Module (Metric) Hobs

Offered in 30°, 37.5°, and 45° NPA.

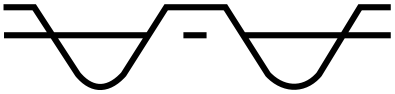
Module	Normal Diameter	Minimum Diameter
0.4	1.875	1.125
0.5	1.875	1.125
0.6	1.875	1.125
0.7	1.875	1.125
0.75	1.875	1.125
0.8	1.875	1.125
0.9	1.875	1.125
1	2.5	1.25
1.25	2.5	1.875
1.5	2.5	1.875
1.75	2.5	1.875
2	2.75	1.875
2.25	2.75	1.875
2.5	2.75	1.875
2.75	2.75	1.875
3	3	2
3.5	3	3
4	3.25	3.25
4.5	3.25	3.25
5	3.5	3.5
6	3.5	3.5
7	3.75	3.75
8	3.75	3.75
10	4	4

(d) Spline Forms

Flat Root:



Fillet Root:



tooling. Hobbing is a “generating” process — the tooth profile is developed in a series of cuts as the hob (a threaded worm with slots or gashes that act as cutting edges (see Figures 5.1 and 5.2) rotates and is fed at an angle to the workpiece. Due to this “swivel” angle the hob must have room to “approach” and “overrun” the needed face width and insure that “full depth” teeth are cut in that area. (This is one of the first things to investigate if load-distribution or noise problems appear.) Allowances must also be made so that the hob does not destroy other features on the part when entering or exiting the cut (see Figure 5.3).

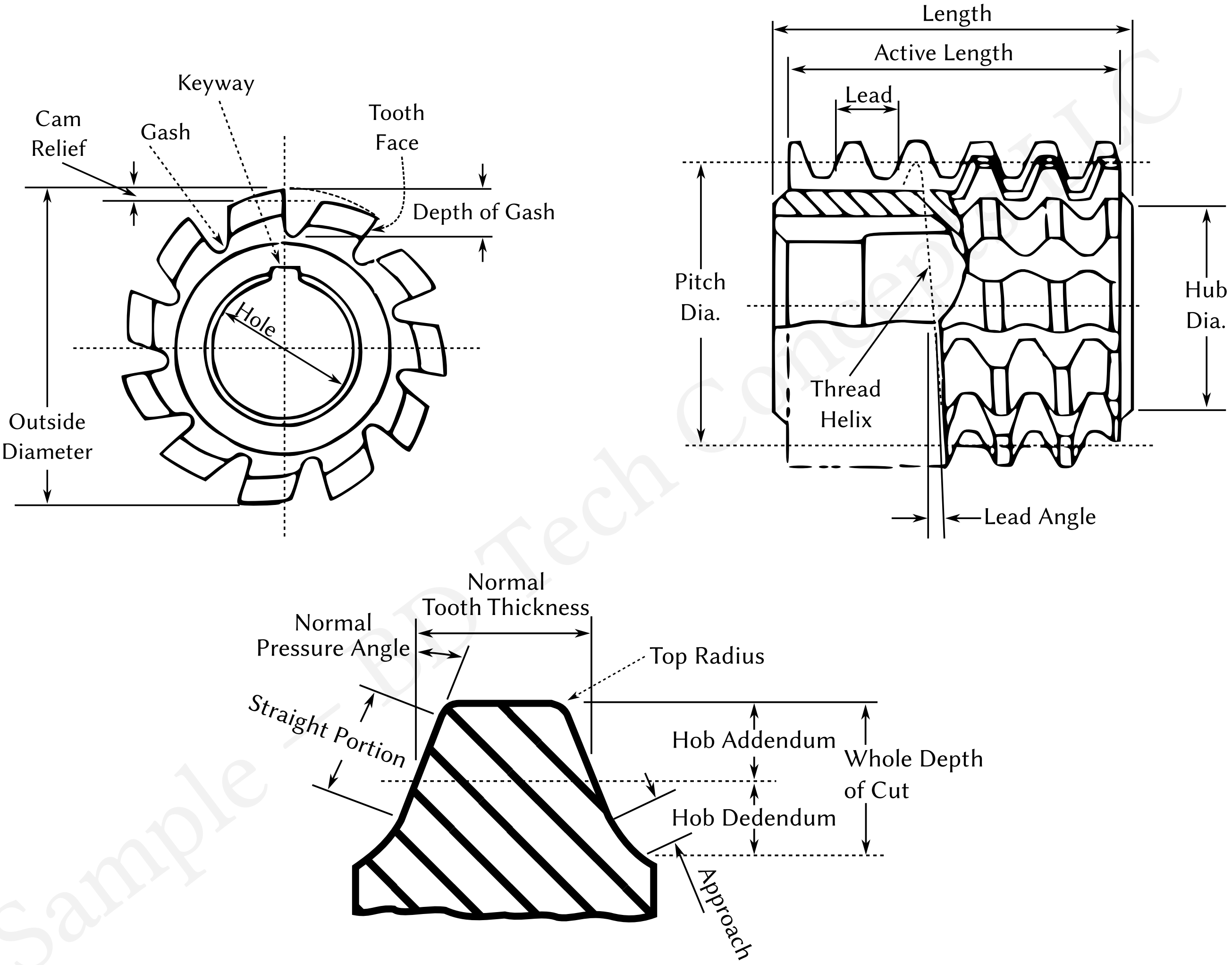
Undercutting is another problem that occurs in the hobbing process. On parts with low numbers of teeth (the limiting number of teeth varies with the pressure and helix angles), the tip of the hob can remove or “undercut” the lower portion of the part tooth, destroying the involute profile and reducing the strength of the tooth. This problem is usually corrected by changing to a higher pressure angle, increasing the number of teeth (with a corresponding reduction in tooth size), or “enlarging” the pinion teeth and “contracting” the gear teeth (also called the “long and short addendum” system). If the number of teeth on your part is less than that shown on Table 5.4, you may want to read the information on undercutting found in the books listed in the reference section of this guide.

Hobbing is used to produce spur, helical, and double-helical gears. The helix angle of helical gears necessitates larger approach, overrun, and clearance allowances. For double-helical gears there is the additional complication of determining the “gap width” required to avoid the hob cutting one side of the gear from damaging the other side when it reaches the end of its cut (see Figure 5.4). The analysis of these situations is quite complex. Several different methods are detailed in the reference books, including graphical techniques that may be adaptable to CAD systems. Where little or no gap width can be allowed, a shaped or assembled double-helical gear can be used. Use of “staggered” rather than “in-line” teeth slightly reduces the gap required for hobbed gears.

Shaping

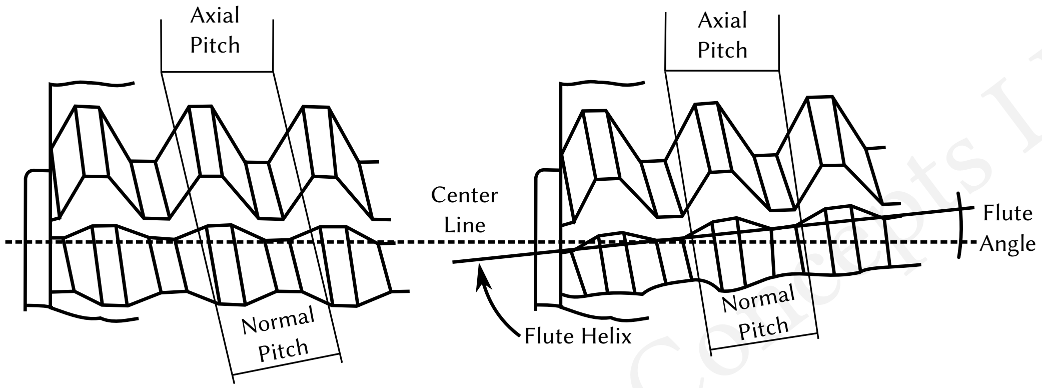
Shaping involves a reciprocating pinion-like cutter (see Figure 5.5) which is rotated and in-fed against the rotating blank to generate the tooth profile. Spur, helical, and double-helical gears can be produced by this method with either internal or external teeth. Cutting-tool availability is not as great as with hobbing, and machine capabilities are far more limited, especially with regard to helix angle. Special “guides” are needed for each helix angle to be cut — at a cost of several thousand dollars each — along with matching cutting tools. To minimize these expenses several standard helix angles have been adopted (23°, 30°, and 45° are most common). Special “herringbone” machines have been developed to cut both sides of a double-helical gear at the same time with little or no “gap” at all. Larger gears (6 DP and lower) can also be produced on “rack”-shaping machines which use a straight “rack” of cutter teeth to generate the tooth profile.

Except for herringbone gears, all shaped teeth require a chip-clearance groove beyond the tooth face (see Figure 5.6). The cutter must also have open access to the start of the cut. Shaped parts can be cut between centers, on an arbor, or in a locating fixture. Fixtures are also used when the gear teeth must be aligned with another feature on the part. It is usually easier to cut the teeth first and then produce the aligned feature, but where this cannot be done it is much simpler to shape the teeth rather than hob them. If alignment is required, remember to make a special note of the relationship to be maintained and a tolerance on that alignment. Normal operating procedure in the gear industry is to assume that no alignment requirement exists unless specifically noted on the drawing. *Any alignment shown*



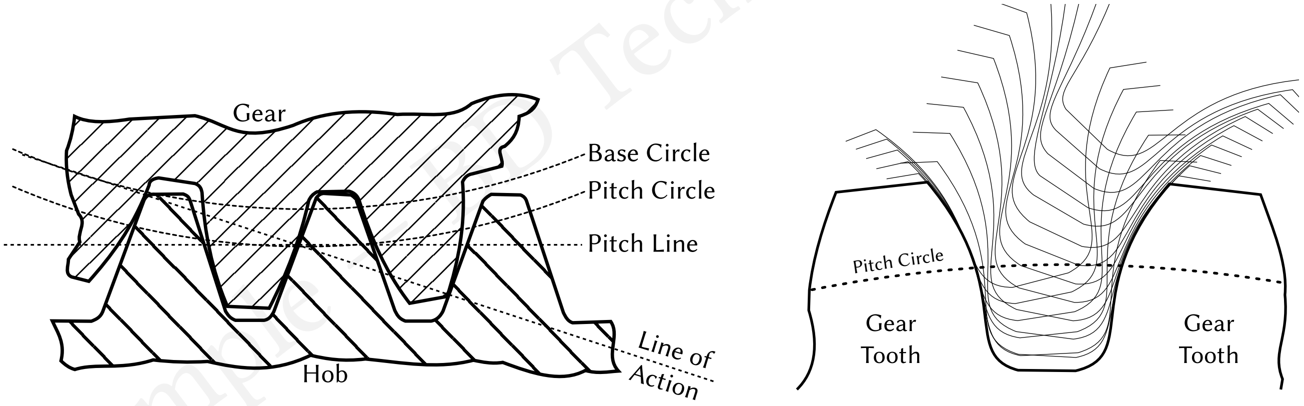
Courtesy of Ash Gear & Supply Corporation

Figure 5.1: Hob Nomenclature — 1



Straight Flute

Helical Flute



The Hobbing Process

The Generating Action of a Hob

Courtesy of Ash Gear & Supply Corporation

Figure 5.2: Hob Nomenclature — 2

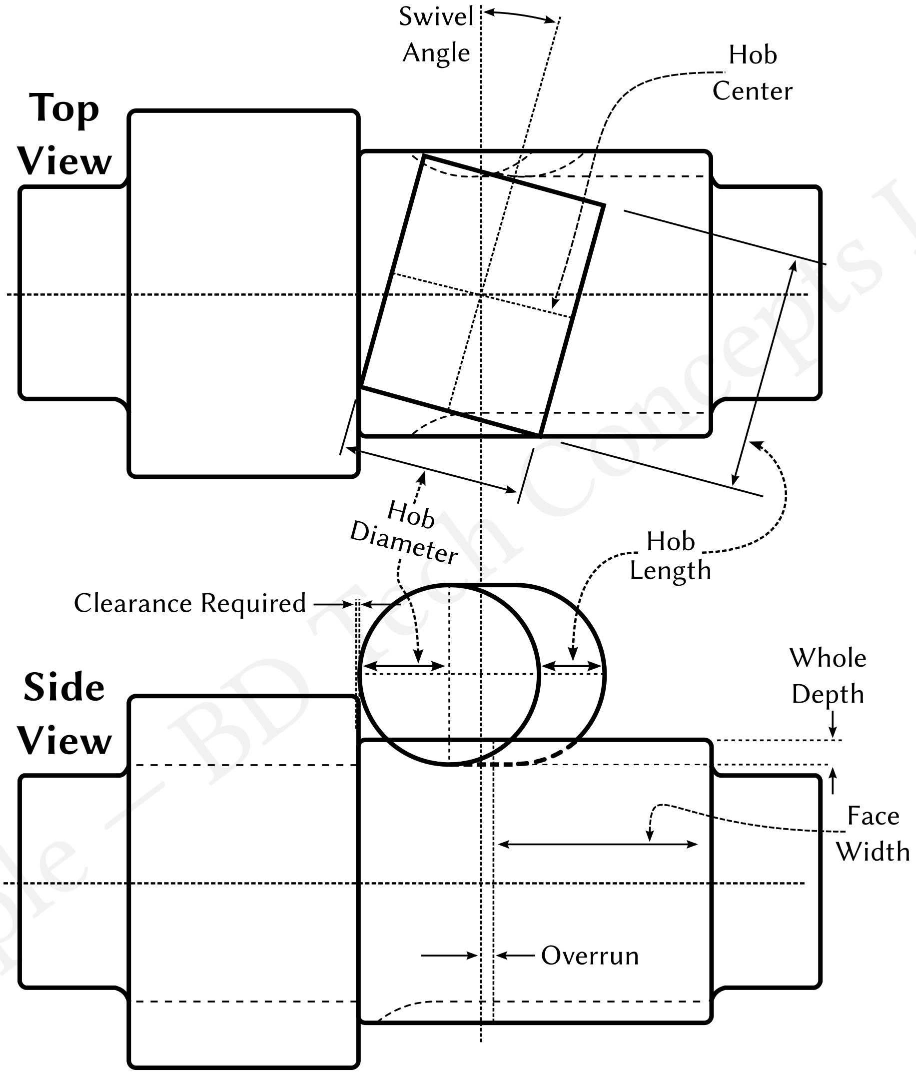


Figure 5.3: Hobbing-Clearance Diagram

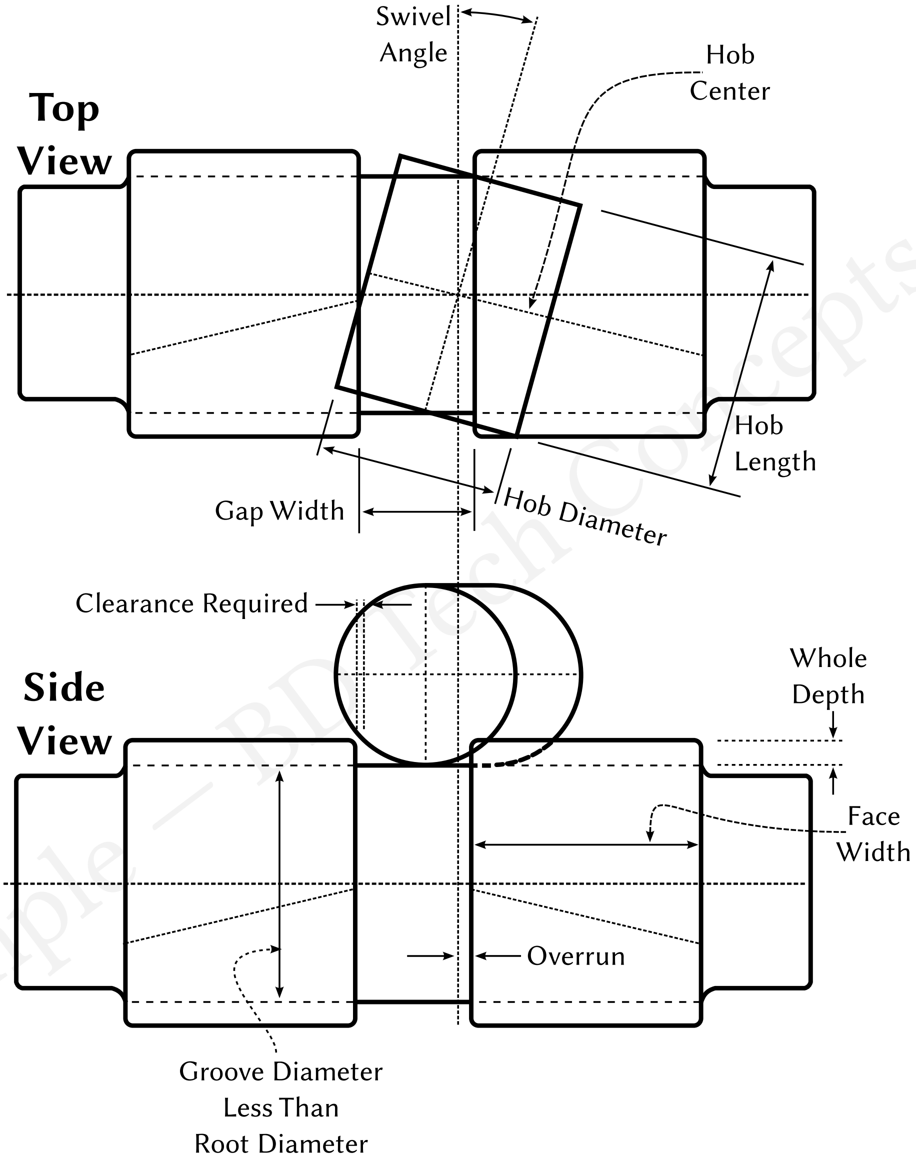


Figure 5.4: Double-Helical Gap-Width Diagram

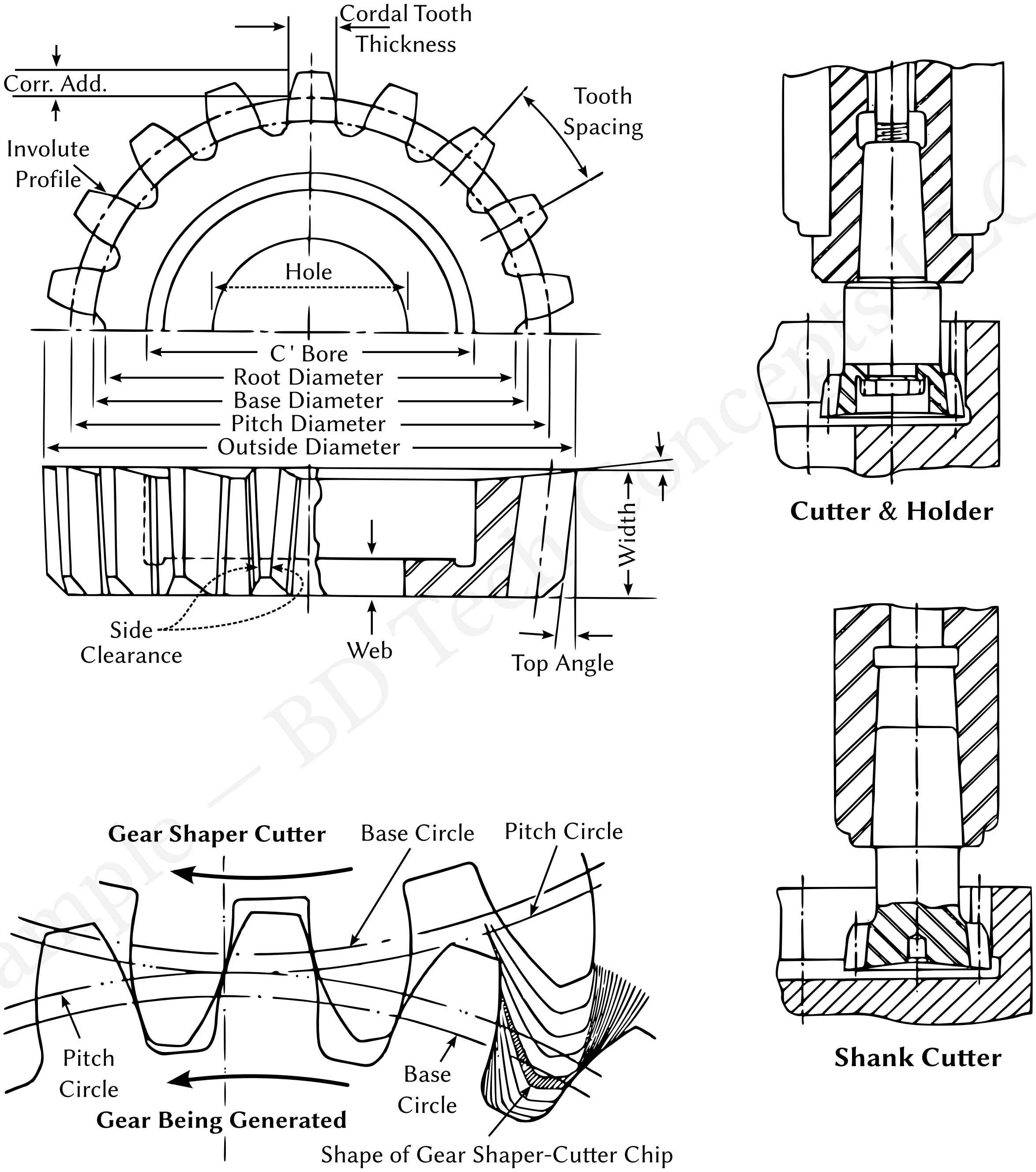
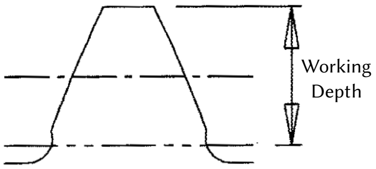


Figure 5.5: Shaper-Cutter Nomenclature

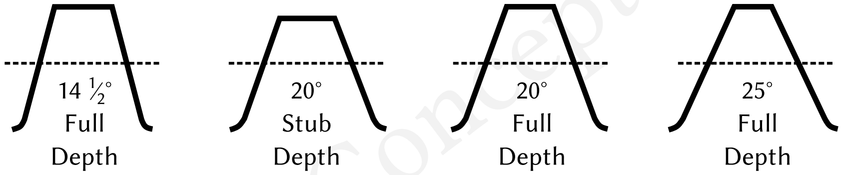
Table 5.4: Minimum Number of Teeth to Avoid Undercutting

Normal Pressure Angle	Whole Depth @ 1 NDP	Helix Angle								
		0°	10°	15°	20°	25°	30°	35°	40°	45°
14.5°	2.157	32	31	30	29	27	25	23	20	17
20°	1.8	15	14	14	13	12	12	11	10	8
20°	2.25	18	18	17	17	16	15	13	12	11
25°	2.25	13	12	12	11	11	10	9	8	8

Undercut tooth:



Relative tooth shape — Same NDP:



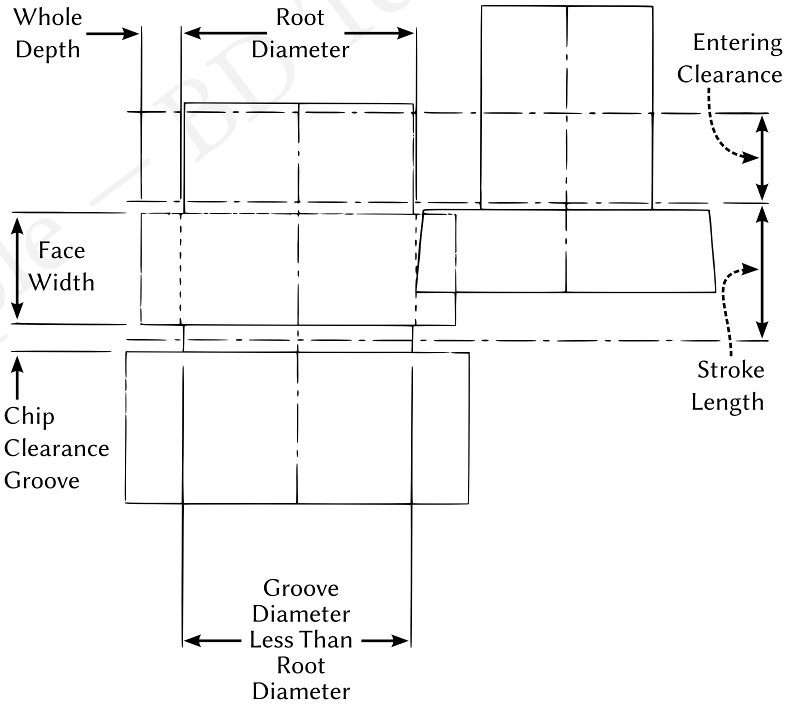


Figure 5.6: Shaper-Cutter Clearance Diagram

on the drawing but not noted is assumed to be a drafting convenience only. Tooth alignment of hobbed teeth is very difficult.

Another important design aspect of the shaping process is the need to relate cutter size to the number of teeth on internal gears to prevent “trimming” of the teeth by the exiting cutter tooth. Table 5.5 shows the minimum number of part teeth that can be cut by a given number of cutter teeth. This varies according to the tooth form, and can be adjusted slightly by enlarging the minor or inside diameter of the internal gear. This can reduce the contact ratio and must be analyzed very carefully. Methods for this are outlined in several of the reference books.

Small shaper cutters are typically made as “shank” cutters (one piece with the tool holder) which have very specific face-width limitations. Wide face widths can cause cutter life and rigidity problems. These parts may be more suitable for the “broaching” method described below. It is best to avoid designing parts that require shaper cutters with less than five teeth.

Broaching

The broaching process is used to produce internal spur gears and splines. A broach having the same shape as the required tooth spaces is pushed or pulled through a pilot hole with each row of teeth removing a little more metal. Some parts may require more than one “pass“ with a series of broaches to reach the final size. The process is very fast and accurate but requires expensive tools and careful blank preparation. Some machines are susceptible to “broach drift” and require final machining after broaching. Part size is limited by the “tonnage” or power capacity of the broaching machine and the length of the broach that can be pulled. Fixtures can be made to align part features and the teeth, or to broach more than one part at a time. Broaching is usually limited to parts under 45 HRC, and tooling design can be very tricky if allowances must be made for heat-treat distortion on parts broached before heat treatment. Broaches are very expensive to make so it is wise to check if your gear manufacturer has an existing broach before finalizing your design. It is important to tell them the length of cut involved as there must be at least two broach pitches in the part at all times to avoid trouble. Give the maximum amount of tooth-thickness tolerance possible, as broaches cannot be adjusted to vary the depth of cut like a shaper.

Lapping

Lapping — the oldest gear “finishing” method — involves running a set of gears with an abrasive fluid in place of the lubricant. This process was developed to adjust for cutting inaccuracies, increase backlash, and improve surface finish. Lapping is no longer widely used, as sophisticated gear inspection techniques have revealed that excessive lapping can destroy the involute form cut into the teeth. Modern gear-cutting equipment can usually produce parts that do not require lapping, and lapping requirements noted on older drawings are frequently ignored. The most common use at lapping today is as a “last resort” in solving field problems or in making very fine adjustments in backlash for pump or instrument gears. In some cases gears are lapped with “dummies” (made of cast iron or another soft material) to replicate the mating part. This reduces the tendency to damage the involute form.

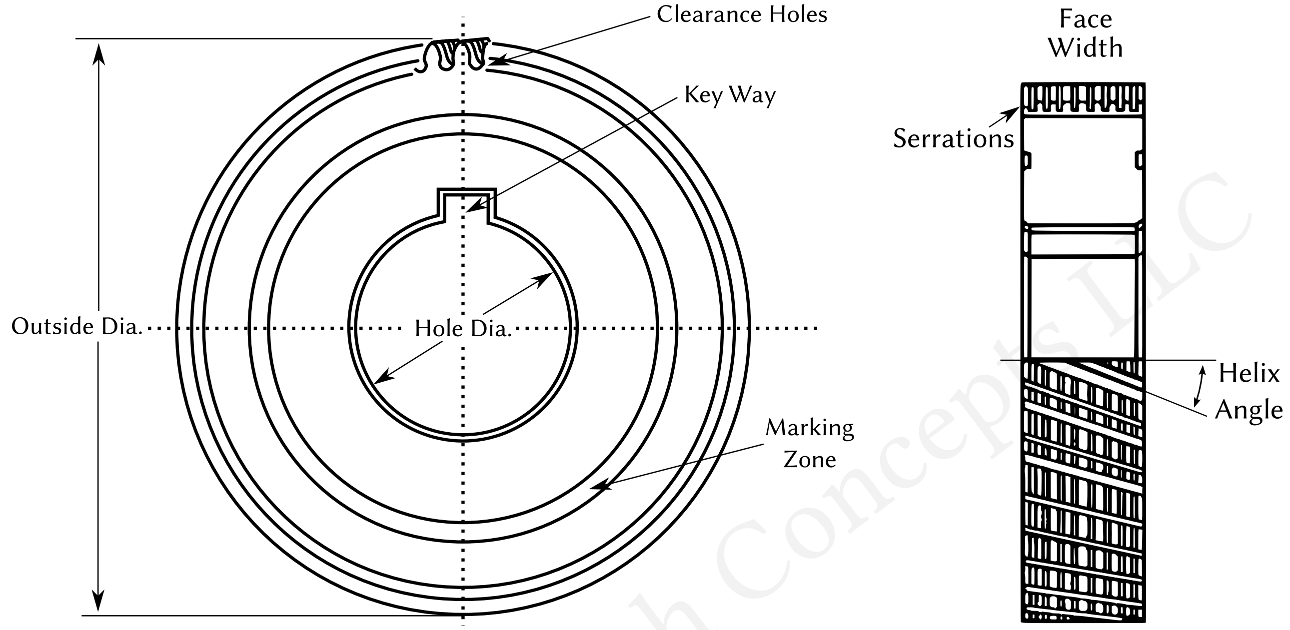
Shaving

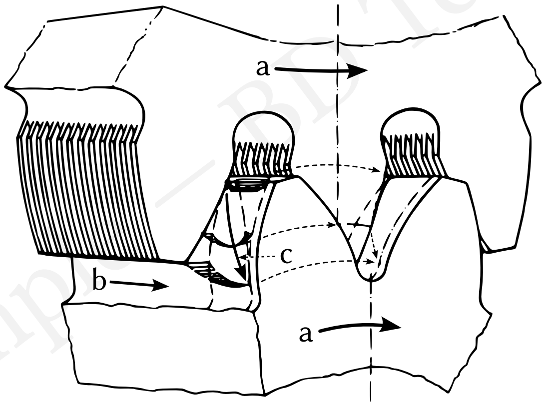
Shaving is a gear “finishing” method that is used to improve surface finish and gear geometry (lead and involute). A serrated gear-like cutter (see Figure 5.7) is rotated and led axially while in mesh with the part. The part teeth must be cut with a special “pre-shave” hob or shaper cutter that finishes the root area at the part but leaves “stock” on the sides of the teeth. The cutter axis is at an

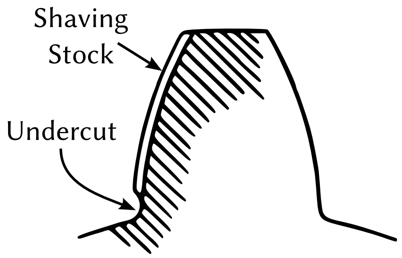
**Table 5.5: Shaper-Cutter Teeth vs.
Minimum Internal Gear Teeth
to Avoid Interference**

# teeth in cutter (N_c)	# teeth in internal gear					
	14.5° FD	20° FD	20° Stub	25° FD	30° FF	30° FR
3	15	11	11	10	9	9
4	18	13	13	12	12	10
5	20	15	15	14	13	11
6	22	17	16	15	14	12
7	24	19	17	17	16	13
8	26	21	18	19	17	14
9	28	23	20	21	18	15
10	30	24	22	22	19	16
11	32	26	23	23	20	17
12	34	27	24	24	21	18
13	36	29	25	25	22	19
14	38	31	26	26	23	20
15	39	33	27	27	24	21
16	41	34	28	28	25	22
18	44	36	30	30	27	24
20	47	38	32	32	29	26
21	49	39	33	33	30	27
24	54	42	36	36	33	30
25	55	43	37	37	34	31
27	58	45	39	39	36	33
28	59	46	40	40	37	34
30	62	48	42	42	39	36
over 30	N_c+32	N_c+18	N_c+12	N_c+12	N_c+9	N_c+6

Note: Small shank cutters (N_c<10) do not produce a true involute form.







Gear Tooth
Undercut required prior to shaving.

(a) Work and cutter rotation
(b) Axial sliding motion caused by crossed axes
(c) Direction of chip removal

(Courtesy of ASH GEAR & SUPPLY CORPORATION)

Figure 5.7: Shaving-Cutter Nomenclature

angle to the part axis which creates a shaving or planing action as the cutter moves axially across the gear face. Spur, helical, and double-helical (with gap) gears can be shaved. Both internal and external teeth can be accommodated if proper tooling can be designed. Tool clearance is an important consideration, as shaving cutters are very fragile and expensive. Internal gears are subject to the same cutter-size limitations discussed in the "shaping" section of this manual. Shaving cutters are often designed for a specific application, and "off the shelf" tooling availability may be limited.

On hobbed parts, care must be exercised to avoid hitting the hob runout area. A technique known as "hob dipping" (feeding the hob past finish depth at the ends of the cut) is sometimes used to minimize this problem (see Figure 5.8). This is similar in principle to crown hobbing. Shaving is often used to provide "crowned" or "tapered" teeth for special applications where shaft misalignment or adjusting backlash is desired. Shaving is most successful on parts less than 50 HRC.

Honing

The honing process is similar to shaving except that the cutters are coated with an abrasive material. As shaving machines can also be adapted to honing most of the limitations discussed above still apply. Honing has been used to produce very finely polished surface finishes (as low as 6 AA) and to finish surface-hardened gears that are not suitable for gear grinding. This is a very "hot" area of gear research and is best studied by reading technical papers and manufacturer's literature.

Gear Grinding

Gear grinding is the "Cadillac" of gear-finishing processes. High accuracy, excellent surface finish, and special features (see Figure 5.9) like crowning, tooth taper, and profile modification (tip relief) are possible with most grinding methods. While there are many different brands of grinding machines (see Figure 5.10), each with a slightly different operating principle, they can be divided into two basic types — form grinders and generating grinders.

Form Grinders

Form grinders employ a thin wheel that has been "dressed" with the profile of the desired tooth space. This method is very versatile and can be used to grind internal and external teeth of almost any type, including non-involute forms. Form grinding is also used to produce racks and gear segments that cannot be done by generating methods. Wheels as small as 1.5 inches in diameter can be fitted on some machines, allowing one piece "cluster" gears and small internal gears to be processed. Dressing the proper form into the wheel requires a high degree of operator skill or an expensive CNC control. Wheels must be re-dressed frequently, adding time to an already slow process. Newer form grinding machines are able to use longer-lasting abrasive-coated steel wheels which may make form grinding more cost competitive. Form grinding should be avoided in the design of new parts if at all possible.

Generating Grinders

One type of generating grinder employs a large diameter (8 to 14 inches is most common) threaded wheel that acts much like an abrasive hob. A relatively simple dressing mechanism is used to maintain a very accurate straight-sided rack with the proper pressure angle and depth in the wheel. The large diameter provides a long life between dressings, but creates clearance problems on many parts (see Figure 5.11). Small diameter "solid-on-shaft" pinions and the pinion on one-piece "cluster" gears are often impossible to grind by this method.

Other generating grinders use either one or two narrow grinding wheels, which simulate a rack. These wheels are very easy to dress but re-

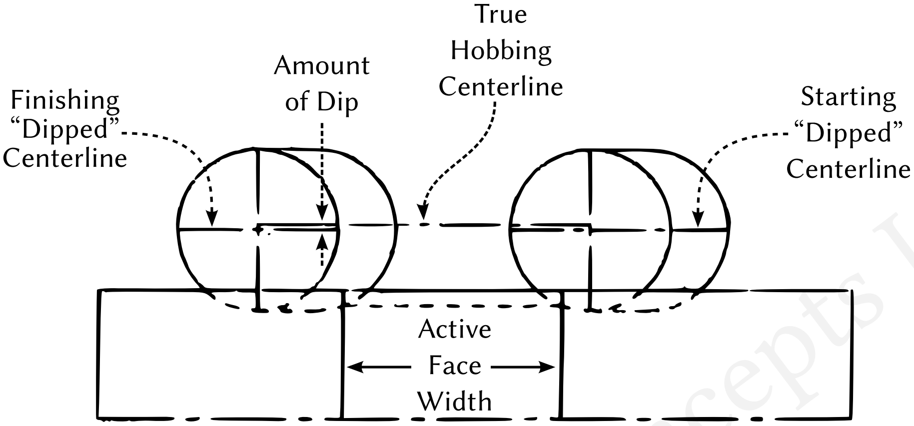


Figure 5.8: Hob-Dipping Diagram — (Pre-Shave)

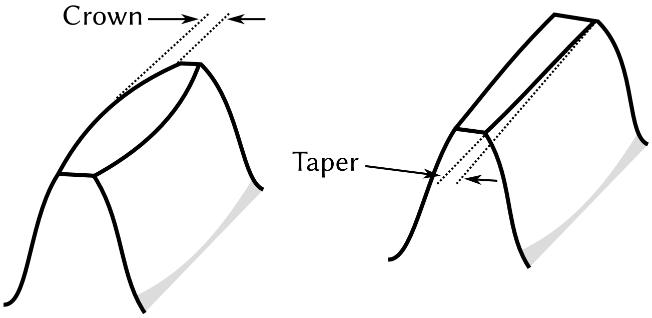
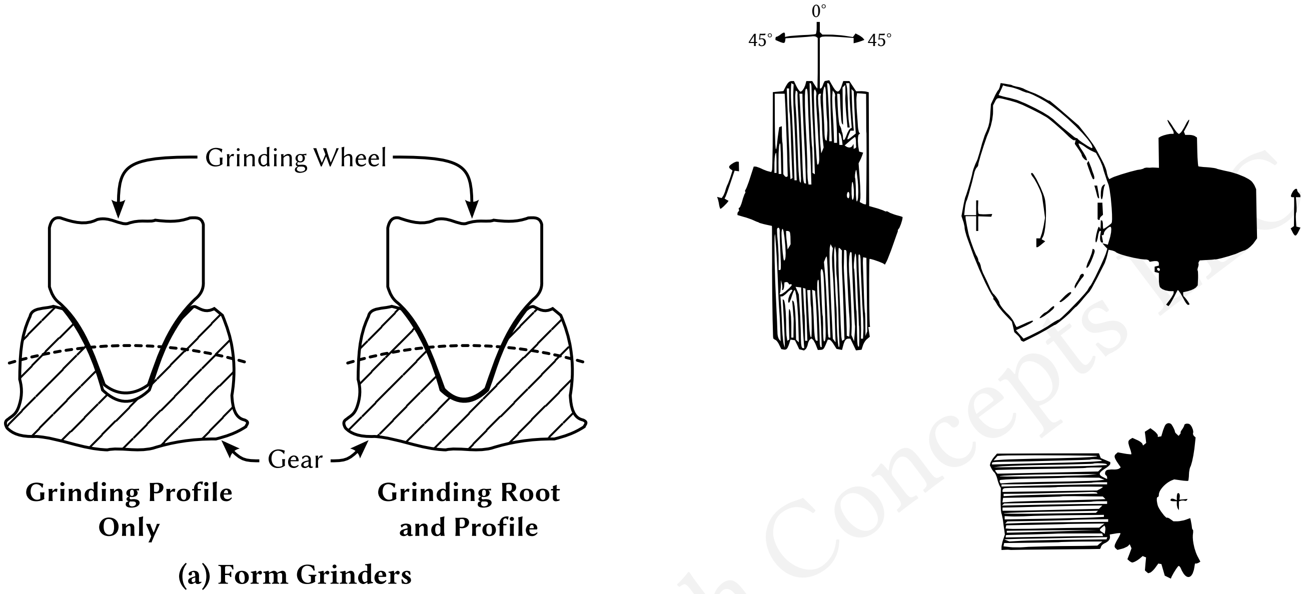
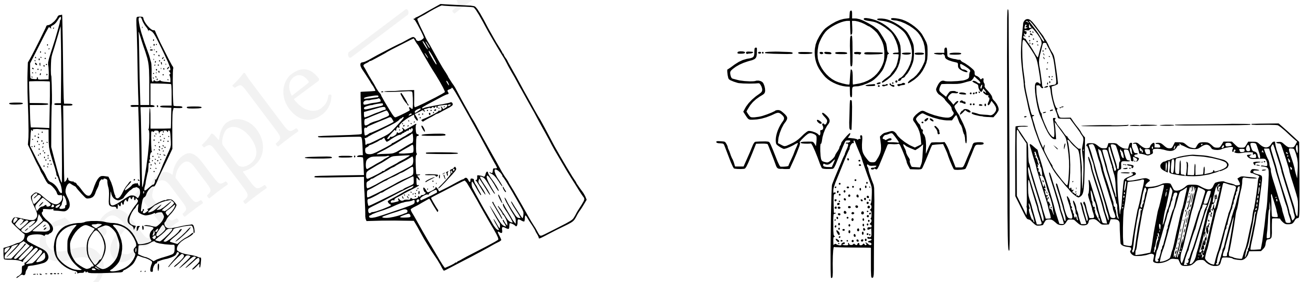


Figure 5.9: Tooth Modifications



(a) Form Grinders (National, Orcutt, Detroit, Kapp, Gear Grind, Michigan)

(b) Threaded Wheel (Reishauer, Okomoto, Sheffield)



(c) Two Wheel (Maag)

(d) Single Wheel (Hoefler, Niles, Pratt & Whitney)

(Courtesy of American Pfauter's *Gear Process Dynamics*)

Figure 5.10: Gear Grinder Types

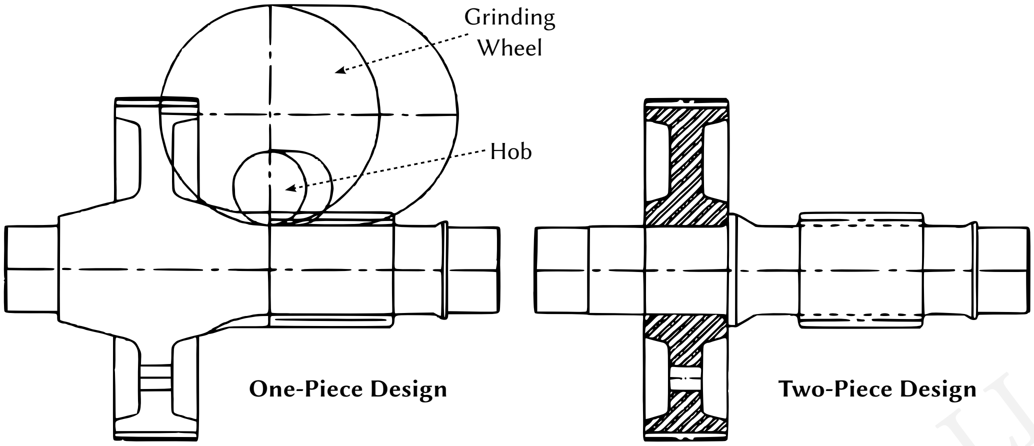


Figure 5.11: Grinding-Wheel Interference on Cluster Gears

quire more frequent attention than the threaded type discussed above. Cycle times are slightly slower also, although they are much faster than form grinding. The same wheel-interference problems are also encountered. For new designs it is best to consult several gear suppliers and read as much as you can on the method to be used before final drawings are prepared.

There are other problems that crop up frequently with all ground gears. Improper feeds, speeds, wheel materials, and coolants can cause grinding cracks and re-tempering (also called soft spots or grinding burns). Nital etching is used as an in-process check on grinding quality, and gear designers are wise to note a nital etch requirement on the drawing. It is also difficult to maintain tight controls on tooth thickness and alignments with other part features because heat-treat distortion may not occur uniformly, and the amount of stock removed from each side of the space may not be equal. These tolerances should be discussed with the supplier before finalizing a design.

Bevel Gears

Bevel-gear-cutting methods fall into two general categories — the reciprocating-blade method for straight bevels, and rotating-cutter methods for straight, spiral, and Hypoid bevels. Bevel gears are probably the most difficult to manufacture. The theoretical "summary" (a computer calculated set of machine adjustments) is just the starting point for developing the proper contact pattern between the gear and pinion. During a production run this contact pattern must be constantly monitored and adjustments made for cutter wear and diameter changes due to resharpening. It is very important that the same mating part or master gear be used for these checks if the parts are to be interchangeable. Many field problems are caused by attempts to use non-interchangeable parts as a gearset. Subtle differences in cutting methods can often result in wide variations in contact pattern. The best policy is to order bevel gears as a set and to replace them as a set. If that is not possible, the use of a master gear and a specified cutting method, complete with a proven summary, is the next-best choice.

Cutter clearance is an important consideration in the design of bevel-gear blanks, especially on parts with a through shaft or hub on the "small end" of the gear (see Figure 5.12). Consult your gear supplier early in the design process, and review all parts that might have this problem. Minor changes in hub or shaft diameters can often result in considerable cost reductions.

Worm Gears

Wormgear sets consist of a threaded worm and a mating gear. The worms can be produced by rolling, milling, or grinding, and usually present no significant manufacturing problems. Wormgears, on the other hand, can be almost as tricky to make as bevel gears. Successful development of the contact pattern and tooth thickness depends on proper initial tool design and accurate adjustment of the hobbing machine to account for cutter re-sharpening. Fly tools, commonly used on low-volume jobs due to lower tool cost, are particularly prone to this problem due to the short life of the single cutting point per lead. This method requires low tool loads and relatively long cycle times to produce an accurate gear. Wormgear hobs are custom-designed to replicate the mating worm and have very distinct limits on the number of times they can be re-sharpened without compromising the tooth geometry. Many field problems are caused by trying to use a hob which has been sharpened below the acceptable limits of outside diameter.

Wormgears are usually checked against a master worm at both the mounted center distance (for backlash) and a "tight mesh" center distance (for total composite error). If no master worm is available, it is acceptable to use a representative mating worm. Cutter clearance is not a problem with wormgear hobbing but part tolerancing should be watched carefully. Excessive runout can cause the contact pattern to "wander" across the face width. Parts cut with a topping hob will have fairly wide variations in "throat diameter" (see Figure 5.13) depending upon how many times the hob has been sharpened. As long as the contact pattern is good and the backlash is within limits, this should not cause a functional problem. Throat diameters should usually be "reference" dimensions.

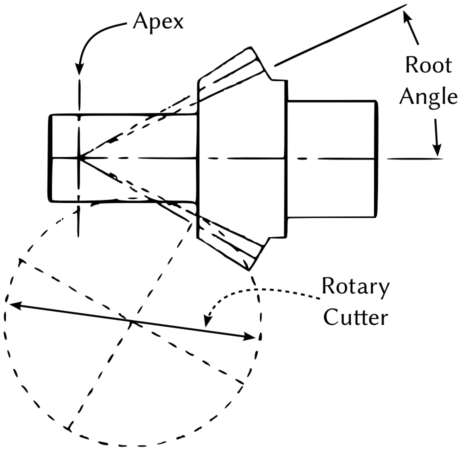


Figure 5.12: Bevel-Cutter Interference with Front Shaft

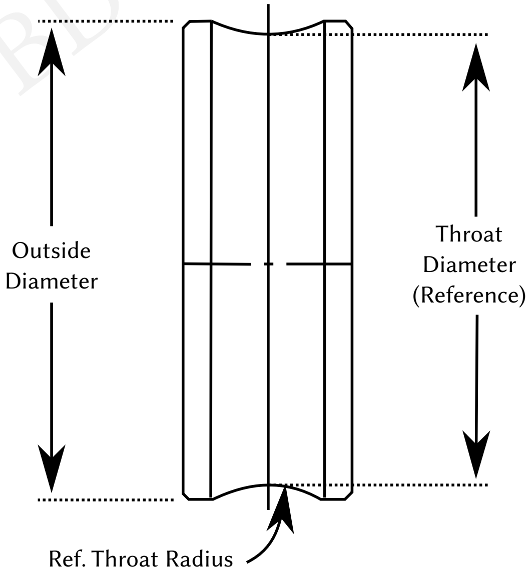


Figure 5.13: Worm-Gear Throat Diameter

Chapter 6

How Should They Be Inspected?

"Quality levels" have been established by the American Gear Manufacturer's Association (AGMA) to provide a common basis upon which to compare parts made by different methods and from different suppliers. The current standard on gear inspection (AGMA 2000) contains information on selecting quality levels, calculating tolerances, and measuring gear elements. When you put an AGMA quality level on a drawing you are specifying that inspections be done in accordance with the provisions of AGMA 2000. The standard outlines many different ways of certifying that a quality level has been met, and the manufacturer is free to select from those methods unless you require specific inspections on your drawing.

Tooth thickness measurements, for example, can be made with five different methods. If you plan to use a particular method for receiving inspection, that is what should be noted on the drawing. The gear manufacturer may then use whatever method he wants for in-process checks, but the final inspection report will contain measurements that are directly comparable to your results.

Most gear purchasers are not equipped to perform detailed gear inspections, and must rely on the supplier to certify the "quality" of the delivered goods. The gear designer has the option of requiring either "composite" or "individual element" (such as lead, profile, spacing, or runout) checks on the drawing, and may request copies of the "charts" (the graphical output of the gear inspection machine) from these checks. Making charts is very time consuming and most gear suppliers pass the cost of this labor on to the purchaser in the form of higher part prices or separate inspection fees. If you require charts be sure to indicate the sampling plan desired. 100% inspections are seldom cost effective. Table 6.1 is an example of a typical sampling plan.

Modern inspection equipment can determine part characteristics with far greater accuracy than manufacturing can make the parts. Some types of gears, such as bevels and worms, have not been subjected to "individual element" checks because of equipment limitations and have always been accepted based upon "composite" methods. Just because it is possible to inspect the individual elements of spur and helical gears does not mean it is practical. It is not uncommon for a gear pair accepted by such methods to have "additive errors" that result in unacceptable performance. Conversely, a pair of "rejected" gears may have "complementary errors" and provide very acceptable performance.

"Elemental" checks provide valuable information for in-process control of manufacturing, but may not be the "best" criteria for final acceptance. The "composite" method of checking a gear against its mate or a master gear on a "tight mesh" center distance considers lead, profile, spacing, and runout errors. Both "flanks" of a tooth space are checked at the same time, however, when in actual operation only one is in mesh at a time. "Single flank", also known as "transmitted error" testing is far more realistic but is not widely available. The author feels that a combination of composite checks and occasional contact-pattern checks (see Figure 6.1) under simulated "assembled" conditions is the most practical way to qualify a gearset and avoid field problems.

Table 6.1: Sampling Plans

Lot Size	1% AQL	4% AQL
2 to 8	100%	1 of 2
9 to 15	100%	1 of 4
16 to 25	100%	1 of 7
26 to 50	1 of 2	1 of 7
51 to 90	1 of 4	1 of 12
91 to 150	1 of 7	1 of 18
151 to 280	1 of 7	1 of 21
281 to 500	1 of 7	1 of 40
501 to 1200	1 of 9	1 of 70
1201 to 3200	1 of 10	1 of 140
3201 to 10,000	1 of 16	1 of 400

Based on Level II-A of Mil-STD-105D.
Modified for in-process inspection.

(a) Worm Gear **(b) Bevel Gear**

Figure 6.1: Bearing Pattern Checks

"Quality" costs when it comes to gears. Before you put a quality requirement on a drawing, make sure you really need it. Attempting to solve your "gear" problems by increasing quality requirements can be expensive and ineffective. The "right" quality level for you is the one that works in your application. It you find that one aspect of your gears (such as lead, profile, spacing, or runout) needs to be controlled more closely than the others, it is your option to tighten the tolerance on just that element. It is not uncommon, for example, to order a Quality 8 gear with Quality 10 spacing as long as it is noted on the drawing. The reference books listed at the end of this manual have extensive discussions on various aspects of gear quality.

Chapter 7

Where Do I Look For Help? — Reference Material

Cutting Tool Catalog
Ash Gear & Supply Company
21380 Bridge Street
Southfield, MI 48034
(313) 357 – 5980

This catalog covers “off-the-shelf” gear-cutting tools, and contains a lot of practical information on gear design.

Machinery’s Handbook
By Erik Oberg, Franklin D. Jones, and Holbrook L. Horton
Industrial Press Inc.
200 Madison Avenue
New York, NY 10157
ISBN 0–8311–1155–0

This “machine-shop bible” contains a good deal of information on gears. While some of it is dated, it still provides a “common denominator” for gear users throughout industry.

Gear Handbook
Darle W. Dudley, Editor-in-Chief
McGraw-Hill Book Company
New York, NY
Library of Congress Number: 61–7304

This 1962 publication is a classic in gear literature, and is a “must-read” for any gear designer’s library.

Practical Gear Design
By D.W.Dudley
McGraw-Hill Book Company
New York, NY
Library of Congress Number: 53–11476

This book may hard to locate, and is somewhat dated, but its tool-design section is an excellent reference for special applications.

Handbook of Practical Gear Design
By Darle W. Dudley
McGraw-Hill Book Company
New York, NY
ISBN 0–07–017951–4

This 1984 revision of *Practical Gear Design* has a lot of new information to offer, including the most complete reference section ever published.

Gear Process Dynamics
By Geoffrey Ashcroft, Brian W. Cluff, Dennis R. Gimpert, and Claude Lutz
American Pfauter Corporation
925 East Estes Avenue
Elk Grove Village, IL 60007

This is the textbook from American Pfauter’s Gear Process Dynamics Clinic, an excellent course for engineers involved in gear manufacturing.

REVISED MANUAL OF GEAR DESIGN
By Earle Buckingham
BUCKINGHAM ASSOCIATES
591 Parker Hill Road Springfield, VT 05156

This three-volume work has some excellent basic information on gear concepts. Section Two covers planetary gears in great detail.

STANDARDS
AMERICAN GEAR MANUFACTURERS ASSOCIATION
1500 King Street, Suite 201
Alexandria, VA 22314
(703) 684 – 0211

AGMA maintains standards on many aspects of gear design, including ratings, materials, inspection, and cutting tools. Don't start an important design project without the latest standards for reference.

ENGINEER TO WIN
By Carroll Smith
MOTORBOOKS INTERNATIONAL
Osceola, WI 54020
ISBN 0–87938–186–8 (pbk.)

While this book is about materials for race cars, it has the most understandable explanation of materials and heat treating I have ever read.

SYSTEMATIC ANALYSIS OF GEAR FAILURES
By Lester E. Alban
AMERICAN SOCIETY FOR METALS
Metals Park, Ohio 44073
ISBN: 0–87170–200–2

If you want to learn why things didn't work out as planned, this is the book to read.

STEEL SELECTION
By Roy F. Kern and Manfred E. Suess
JOHN WILEY & SONS, INC.
New York, NY
ISBN: 0–471–04287–0

This book may contain more than you ever want to know about steel selection, but it is easy to read and explains a great deal about why we use the steels that have become "popular".

DESIGN OF WELDMENTS
By Omer W. Blodgett
THE JAMES F. LINCOLN ARC-WELDING FOUNDATION
P.O. Box 3035
Cleveland, Ohio 44117

If you are going to design or use welded gear blanks or housings, you are going to need a copy of this book.

PLASTICS GEARING
ABA/PGT PUBLISHING
1395 Tolland Turnpike
Manchesler, CT 06040

For information on plastic gears, this is the book to read.

Chapter 8

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Chapter 9

About the Author

CHARLES D. SCHULTZ has been active in the gear industry since 1971. A registered professional engineer in Wisconsin and Pennsylvania, Mr. Schultz has presented four papers at AGMA Fall Technical Meetings. His work has included engineering over five hundred custom gearboxes, supervising a large industrial-engineering department, managing a custom-drive-system division, designing heat-treat equipment, conducting field-service operations, writing a product catalog, supervising a sales and marketing department, cost estimating, and teaching gear and heat-treat courses for co-workers and customers.

He has experience with a wide range of gear drives ranging from medical devices to bridge machinery, including metal-processing equipment and wind-turbine gearboxes.

Since 2008 he has owned and operated an engineering consulting firm, BEYTA GEAR SERVICE.

Mr. Schultz is a technical editor and blogger for *GEAR TECHNOLOGY* magazine.