Finishing of Conical Gears by Pulsed Electrochemical Honing

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CHAPTER ONE

INTRODUCTION

1.1 Introduction to Gears

The gear, one of the most important mechanical elements, possibly even surpassing the wheel, in human civilization, is used to transmit motion and/or power mechanically and positively (i.e. without slipping) with and without changes in the direction and speed of rotation by the successive engagements of teeth cut on the periphery. It is an economical method for the transmission of a higher power with more accuracy. Gears have been receiving the special attention of the technical community for more than two millennia because they are an essential element of many machines, equipment and devices. They can be classified according three criteria:

(1) according to the location of teeth: (a) on the periphery of the gear blank, i.e. external gears and internal gears; (b) along the radial direction on the gear blank, i.e. face gears;
(2) according to the relationship between axes of transmission: (a) *cylindrical* gears for transmission between *parallel* shafts, i.e. spur gear, helical and double helical or herringbone gears; (b) *conical* gears for transmission between *intersecting* shafts, i.e. straight bevel, spiral bevel, zero-bevel, crown bevel and miter bevel gears; (c) gears for transmission between *nonparallel* and *non-intersecting* shafts, i.e. hypoid gears, crossed helical gears and worm and worm wheel;
(3) according to motion transmission: (a) rotation to rotation, (b) rotation to translation and vice-versa (i.e. rack and pinion).

Gear drives are preferred for various power and motion transmission purposes due to their compactness and higher reliability. More than 10 billion gears are manufactured annually and consumed in various applications in almost all industries (Radzevich, 2012). Some applications worth mentioning are:

- Private transportation (i.e. cars, trucks, tractors, motor-cycles, scooters, etc.)
- Public transportation (i.e. buses, trains, subways, mine cars, etc.)
- Aerospace (i.e. high-speed aircraft engine)
- Marine (i.e. high-power high-speed marine engine, navy fighting ships)
- Defence (i.e. guns, helicopters, tanks, radar applications)
- Earth-moving vehicles
- Different types of machine tools
- Oil and gas industry (i.e. oil platforms, pumping stations, drilling sites, refineries and power stations)
- Industrial applications (i.e. power transmission, construction equipment, agriculture machinery, equipment and machines used in mining, cement manufacturing, steel manufacturing, food processing, sugar manufacturing and other industries)
- Home appliances (i.e. washing machine, food mixtures, fans, etc.)
- Mechanisms, toys and gadgets

Despite their excellent market position, there are some increasing requirements for further improvement in gear drives, namely: (i) increase in power transmission capacity; (ii) reduction in running noise, toxic emission and price; (iii) increase in reliability and service life; (iv) easy disposal and material recycling of the used gears; and (v) integration of systems such as data acquisition, logical control, safety system. Gear failure is an unpredictable and catastrophic phenomenon and there are various reasons responsible for different types of gear failure. Gear failure can be categorized into two types, i.e. failure related to lubrication and failure related to non-lubrication. Table 1.1 presents different modes of gear failure. Prevention of premature failure of gears requires careful consideration of the interrelationship between following aspects of gears: (i) tooth geometry; (ii) tooth motion; (iii) forces (static and dynamic) acting on a gear tooth; (iv) material; (v) physical and chemical characteristics of the lubricant; (vi) operating environment; and (vii) surface characteristics (i.e. surface quality and surface integrity). Of these, the first six aspects depend on the design and operating environment of the gears whereas the last factor depends on the surface characteristics of the gears.

Table 1.1: Different modes of gear failure (Davis, 2005).

Failures related to lubrication		**Failures related to non-lubrication**		
Overload	Bending fatigue	Hertzian fatigue	Wear	Scuffing
1. Brittle fracture 2. Ductile fracture 3. Plastics deformation • Cold flow • Hot flow • Indentation • Rippling • Ridging • Bending	1. Low cycle fatigue (< 1000 cycles to failure) 2. High cycle fatigue (> 1000 cycles to failure)	1. Pitting • Initial • Superficial • Destructive • Spalling 2. Micro-Pitting • Frosting • Gray stanning • Peeling 3. Sub-case fatigue	1. Adhesion 2. Abrasion 3. Corrosion 4. Fretting	1. Scoring 2. Galling 3. Seizing 4. Welding

1.2 Performance Characteristics of Gears

The performance characteristics of a gear include its load-carrying capacity, service life, operating performance, surface characteristics, wear characteristics, transmission characteristics and noise generation characteristics. All are significantly affected by the surface characteristics of a gear, which has two major components: (i) ***surface quality***, which includes surface finish, micro-geometry (i.e. form and location errors), tooth flank topology and wear characteristics; and (ii) ***surface integrity*** aspects. Table 1.2 presents the effects of surface characteristics on the various performance characteristics of a gear. It is evident from this table that improvements in the surface characteristics of a gear help improve its service life, operating performance, wear characteristics and transmission characteristics and reduce its noise generation.

Table 1.2: Effect of surface characteristics on various performance characteristics of a gear

Objective: Improving service life, operating performance and wear characteristics	**Objective:** Improving transmission characteristics and reducing noise generation
• Reduce surface roughness of gear teeth flank surfaces	• Reduce surface roughness of gear teeth flank surfaces
• Reduce coefficient of sliding friction and friction forces to improve wear characteristics	• Reduce errors or deviations in micro-geometry of the gear
• Improve microstructure	• Remove sharp corners from working profile of the gear teeth
• Increase fatigue life	• Increase wear resistance

1.2.1 Surface Quality

The surface quality of gears is evaluated in terms of surface roughness, micro-geometry, tooth flank topology and wear characteristics. Errors in micro-geometry and poor surface finish contribute approximately 20% and 10% to noise generation and poor transmission characteristics of gears, respectively, making them the most dominant contributors. They also lead to errors in motion transfer, backlash between the meshing gear pairs, large dynamic forces during power transmission and incorrect velocity ratios. Poor surface quality also results in the excessive wear of the gear tooth flank, which adversely affects the service life and operating performance of gears during their use. Therefore, a gear tooth surface should have an excellent surface quality for smooth, noiseless power and/or motion transmission and to improve its service life and operating performance.

1.2.1.1 Surface Roughness

Surface roughness affects several functional attributes of gears, such as friction, wear and tear, ability to distribute and hold a lubricant. The selection of appropriate gear finishing processes is critical to getting the desired surface finish on gear tooth flank surfaces. Surface roughness is evaluated using a roughness profile obtained by using either contact type or non-contact type surface roughness measuring equipment.

Fig. 1.1(a) shows the unfiltered primary profile (known as the P-profile) obtained for traverse length (L_t), which consists of pre-travel length, evaluation or assessment length (L_n) and post-travel length. The cut-off length (λ_c) of a profile filter distinguishes between the wavelengths belonging to surface roughness and waviness. Sampling length (L_r) is the reference length for roughness evaluation and it is equal to cut-off length. Evaluation length (L_n) is that part of the traverse length over which surface roughness parameters are determined. Standard roughness evaluation comprises of a minimum of five consecutive sampling lengths (L_r). Average surface roughness, maximum surface roughness and depth of surface roughness are the most commonly used parameters to evaluate the surface roughness of the gears.

Average surface roughness (R_a) is the universally recognized parameter of surface roughness. It is the arithmetic average of absolute values of roughness profile ordinates from the mean line of the profile and is measured within the assessment length (L_n), as depicted in Fig. 1.1 (b). *Single roughness depth* (R_{zi}) is the vertical distance between the highest peak and the deepest valley of the profile within a sampling length (Fig. 1.1(c)). *Depth of surface roughness (R_z)* is the arithmetic mean of single roughness depths R_{zi} of consecutive sampling lengths. *Maximum surface roughness* (R_{max}) is the distance between the highest peak and the deepest valley of the roughness profile within the evaluation length (L_n).

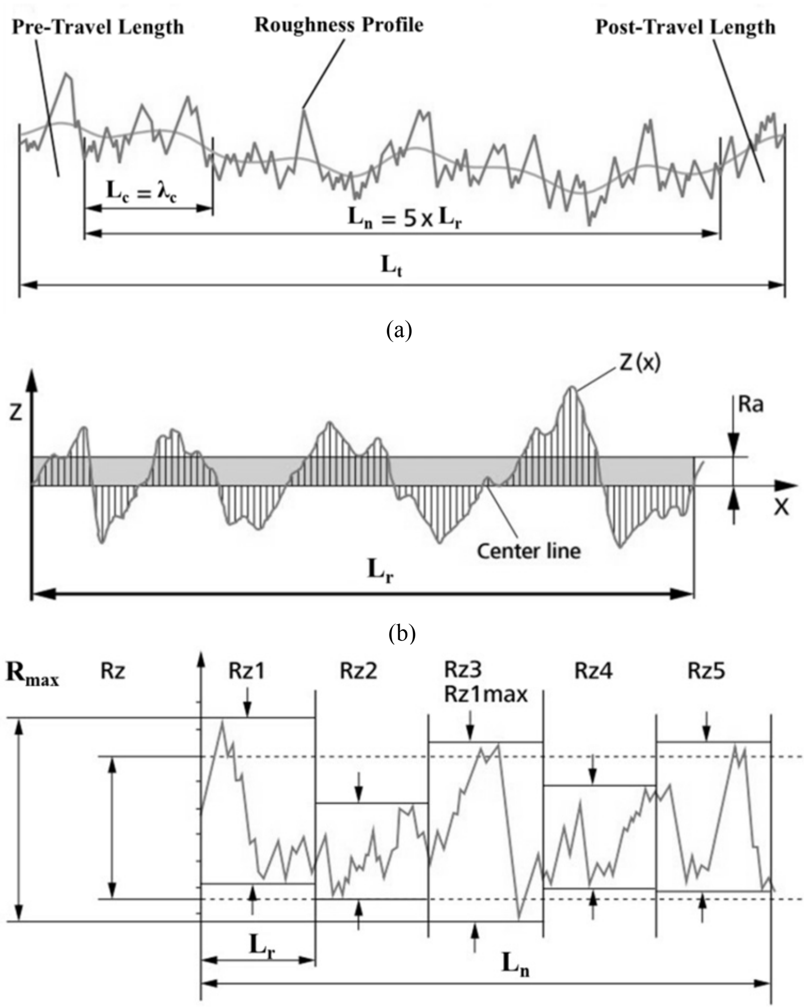


Fig. 1.1: Photographic representations of (a) unfiltered primary profile (P-profile); (b) average surface roughness; and (c) maximum surface roughness and depth of surface roughness.

1.2.1.2 Micro-geometry

The micro-geometry of a gear is evaluated in terms of form error and location error. Gupta and Jain (2014) mentioned that higher values of form error and location error in a gear lower its load-carrying capacity and increases noise and errors in motion transfer during its use. Total profile error and total lead error are two components of form error. *Total profile error* (F_α) defines the form and location of the involute profile of a gear. Fig. 1.2 depicts the concept of its measurement. It is evaluated tracing the involute profile from root to tip in the middle of the face width. Total profile error significantly affects the noise generation characteristics of a gear.

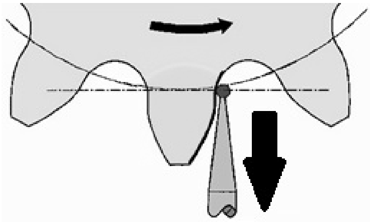


Fig. 1.2: Concept of measurement of profile error of a gear.

The *total lead error* or *total alignment error* (F_β) of a gear defines the form and location of its tooth flank. Fig. 1.3 shows the concept of its measurement and the computation procedure of it and its components. It is evaluated by tracing the gear tooth flank surface along the pitch line, i.e. tracing at pitch point along the face width 'F_w' of the gear. It is the most influential factor determining the load-carrying capacity of a gear.

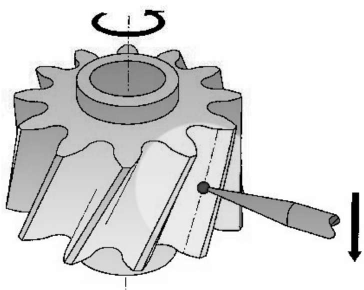
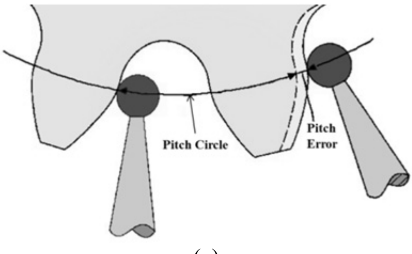
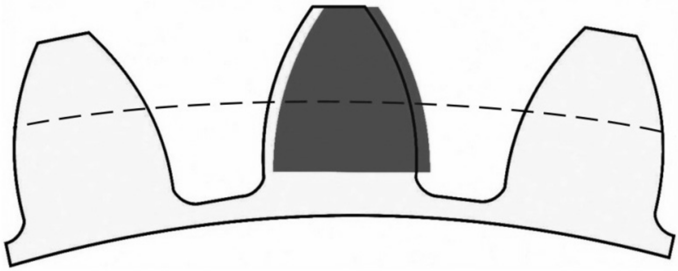


Fig. 1.3: Concept of measurement of lead error of a gear.

Location error consists of pitch error and the runout of a gear. These errors significantly affect the motion transfer characteristics and noise generation characteristics of a gear. Pitch error and its components are evaluated along the pitch circle at the middle point of the face width [Fig. 1.4(a)]. It describes the middle location of all right and left flanks with respect to each other. It has three components: (i) *single pitch error* (f_p) is the difference between the actual and nominal angular positions of two respective flanks on the two consecutive gear teeth [Fig. 1.4(b)]; (ii) *adjacent pitch error or pitch-to-pitch deviation* (f_u) is the maximum difference between the angular deviations of any two adjacent right flanks or left flanks; and (iii) *cumulative pitch error* (F_p) *or index error* is the difference between the summation of the theoretical values of pitches and the summation of the actual values of the pitches of all the teeth of a gear. It represents the differences between the most positive pitch and the most negative pitch values (i.e. vertical distance between the highest and lowest points of the pitch variation curve) of all the teeth of a gear, as shown in Fig. 1.4(c). *Runout (F_r)* describes the radial location of all the teeth of a gear with respect to its pitch circle. It is the maximum difference between the actual radial positions of all the teeth measured with respect to their nominal radial position, as shown in Fig. 1.4(d). It is evaluated along the pitch circle at the middle point of the face width.



(a)



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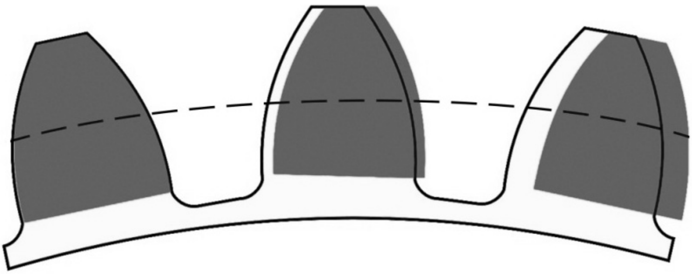
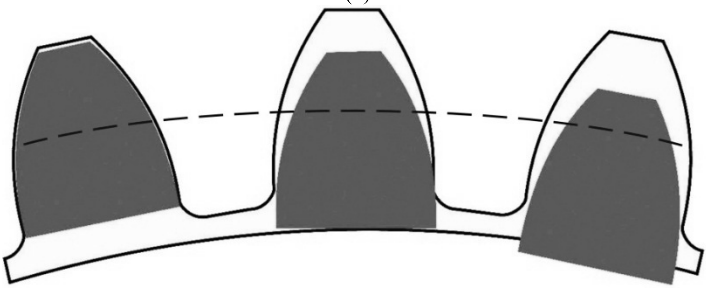


(c)



(d)

Fig. 1.4: Concept of (a) measurement of pitch error and runout; (b) single pitch error; (c) cumulative pitch error; and (d) runout.

1.2.1.3 Gear Tooth Flank Topology

The study of the topology of entire flank surfaces of a gear and comparing with its ideal or theoretical flank surface is a very important aspect of gear surface quality. It helps studying the distribution of material over the flank surface of the gear teeth. It shows non-uniform material distribution in the form of peaks and valleys over the gear flank surface from which vertical deviations can be computed at the toe end and heel end of a gear tooth flank. Gear tooth flank topology becomes a very important aspect in judging the overall quality of the conical gears for which the measurement of errors in profile and lead is not possible due to continuously varying face width. In gear-finishing processes, tooth flank topology measurement and analysis help in finding the effectiveness of the process to smooth out the non-uniform distribution of material on the gear tooth flank surface.

1.2.1.4 Wear Characteristics

The wear of a gear is a surface phenomenon in which some material is lost gradually and generally non-uniformly from the contact surface of a gear. Wear characteristics help define the service life, operating performance and mechanical efficiency of a gear. They are evaluated in terms of wear rate, the coefficient of sliding friction and friction force. The mechanical efficiency of a gearing system increases with the decrease in the coefficient of sliding friction 'μ'. It may reach up to 99.5% if the coefficient of sliding friction becomes less than 0.05 for the gears (Moldovean et al., 2011).

1.2.2 Surface Integrity

Surface integrity is the description and control of many possible alterations produced in a surface layer during manufacturing, including their effects on the material properties and the performance of the surface during the service. It is an assessment of the overall engineering quality of a surface and its ability to perform the required service functions. It is concerned with the effects a manufacturing process produces below the visible surface. Sub-surface characteristics occur in various layers or zones and changes can be due to mechanical, metallurgical, thermal, chemical and electrical causes. All the manufacturing processes significantly affect the workpiece material and its properties but the bulk of currently available data relates to conventional and unconventional material removal processes. The main causes of alternations to a surface during material removal process are: (i) plastic deformations or mechanical strain; (ii) high temperature and temperature gradients; (iii) chemical reactions or absorption on nascent machined surface; (iv) excessive electrical currents; (v) excessive energy densities during processing.

Fatigue failures often initiate at or just below the surface of a component, i.e. fatigue behaviour is sensitive to the surface condition. Also, when considering stress corrosion resistance, the surface condition of a component is a primary factor in determining susceptibility to attack and possible subsequent part failure. Control of surface integrity adds to the cost of the manufacturing process therefore analysis of surface integrity must be considered only in the manufacture of highly stressed components used in applications involving human safety, high cost and predictable component life. High performance gears are subjected to extreme loading conditions and hostile operating environments and thus require very high quality. Most of the conventional manufacturing and finishing processes for gears deteriorate their surface integrity by inducing undesirable sub-surface (generally up to depth of 0.5 mm below the surface) damage such as micro-cracks, micro-pits, craters, laps, tears, hardness alternation, plastic deformation, uncontrolled surface hardening, tensile residual stresses, grain size alternation, heat-affected zones, recrystallization, oxidation, inter-granular attack, alloy depletion, selective dissolution, etc. The poor surface integrity of a gear adversely affects its fatigue behavior, wear characteristics, service life and operating performance. Analyses of microstructure, micro-hardness and residual stresses are most commonly used to assess the surface integrity of a gear after its manufacturing and/or finishing. Careful considerations and the selection of appropriate manufacturing and finishing processes are required to improve the surface integrity of a gear.

1.2.2.1 Microstructure

Details of the material surface visible either by the naked eye or under low magnification are known as macrostructure and useful information can often be gathered from them also. Those material details that require high magnification to be visible are referred as microstructure. Study of microstructure is an important aspect of investigation in almost all manufacturing and finishing processes to identify the changes occurring in the grain structure, grain size, phases present, chemical homogeneity, phases distribution, surface damages (i.e. mechanical, thermal, chemical or electrical), and elongated structures formed by plastic deformation as a consequence of these processes. Different types of microscopes (i.e. optical, electron or scanning electron) can be used for the examination of microstructure depending on the resolution of the required details. Optical microscopes are used for resolutions roughly the wavelength of light (i.e. about half a micron). An electron microscope is used for detail down to atomic resolution. Scanning electron microscopy (SEM) is used to examine the surface using an electron beam and the reflected beam of electrons is collected and then displayed at the same scanning rate. The image that appears on the screen represents the surface features of the specimen and can be photographed.

1.2.2.2 Micro-hardness

Evaluation of the micro-hardness of a gear helps identify changes in its surface hardness before and after manufacturing, finishing or heat treatment process. It also helps to assess the depth of its case hardening.

Micro-hardness can be measured using Vicker, Knoop and Rockwell hardness testing, the most commonly used methods for measuring micro-hardness.

1.2.2.3 Residual Stresses

Gears are subjected to alternate and dynamic loading conditions and consequently fatigue failure of a gear is a common phenomenon. Imperfections in gear design, material properties (i.e. hardness, strength, depth of case hardening, microstructure etc.), meshing arrangements and gear shaft alignments are causes of early fatigue in gears. Therefore, gears are always designed using the fatigue strength of their material. Improvement in the fatigue behaviour of gears plays a crucial role in defining their load-carrying capacities and reliability. Fatigue strength can be improved by inducing compressible residual stresses. X-ray diffraction (XRD) is widely used for the measurement of residual stress in material.

1.3 Materials, Manufacturing Processes and Standard for Gears

Materials used for manufacturing the gears depend on various criteria such as application, shape, size, service, peripheral speed, required accuracy, type of manufacturing process, load-carrying capacity, wear resistance, allowable stress, etc. The following are some guidelines that can be used for selecting a gear material:

- Cast iron is a popular gear material due to its good wear resistance, good lubrication, relatively good machinability and ease of producing complicated shapes by casting it. It is used for manufacturing large gears of complicated shapes.
- Steel is sufficiently strong and possesses good resistance to abrasive wear of the gears.
- Cast steel is used where stress on the gear is higher and gear geometry is difficult to manufacture.
- Plain carbon steels are used for manufacturing the gears for industrial applications due to the combination of their toughness and strength.
- Alloy steels are used where higher gear tooth strength and lower wear of gear flank surface are desired.
- Aluminum is used for manufacturing light-weight gears.

- Non-metallic materials are used for manufacturing gears for noiseless operation at higher peripheral speeds.

Conventional gear manufacturing processes are classified into two major categories, i.e. generative type and non-generative type gear manufacturing. Table 1.3 presents the different gear manufacturing processes for cylindrical and conical gears.

Table 1.3: Different manufacturing processes for cylindrical and conical gears

Manufacturing processes for cylindrical gears		**Manufacturing processes for conical gears**	
Generative type	Non-generative type	Generative type	Non-generative type
Gear hobbing 1. Aerial hobbing 2. Radial hobbing 3. Tangential hobbing	**Gear casting** 1. Sand casting 2. Permanent mold casting 3. Centrifugal casting 4. Investment casting 5. Die casting 6. Shell molding	Face mill cutting	Template machining
		Face hob cutting	Format cutting
		Interlocking cutters	Helix-form cutting
		Revacycle	Cyclex method
Gear shaping 1. Rack type cutter 2. Pinion type cutter	**Gear forming** 1. Gear rolling 2. Extrusion 3. Stamping 4. Forging 5. Cold drawing 6. Injection molding 7. Fine blanking	Two-tool generators	
		Special processes for gear manufacturing	
Gear milling 1. Disc type cutter 2. End mill cutter		1. Gleason method 2. Straight bevel gear cutter 3. Spiral bevel gear cutter	
	Powder Metallurgy		
Advanced processes for gear manufacturing			
1. Electrical discharge machining (EDM) 2. Wire electrical discharge machining (WEDM) 3. Additive layer manufacturing (ALM) processes			

There are different international standards for expressing gear quality. Some standards worth mentioning are Deutsches Institut fur Normung (DIN) of Germany, American Gear Manufacturing Association (AGMA), Japanese International Standard (JIS), Korean Standard (KS), Italian Organization of Standardization (UNI) and British Standards Society (BSS). The two most commonly used standards in industries to define gear quality are AGMA 3900 and DIN 3963. Table 1.4 presents typical applications of gears of different accuracy levels and corresponding gear quality expressed in both AGMA 3900 and DIN 3963 standards.

Table 1.4: Applications of gears with respect to geometric accuracy.

Accuracy level	Gear standard		Typical applications
	AGMA 3900	**DIN 3963**	
AA: Ultra-high accuracy	14 or 15	2 or 3	Military navigation, precision, instruments, computer, equipment
A: High accuracy	12 or 13	4 or 5	Instruments, aircraft engines, turbines, professional cameras, Precision machine-tool speed drives, automotive transmissions, high-speed machinery.
B: Medium-high accuracy	10 to 11	6 to 7	
C: Medium accuracy	8 to 9	8 to 9	
D Low accuracy	6 or 7	10 or 11	Appliances, hand tools, pumps, commercial clocks, farm machines, fishing reels, hoists, slow-speed machinery.
E Very low accuracy	4 or 5	12	

1.4 Conventional Finishing Processes for Gears

The conventional manufacturing processes of gears do not yield acceptable surface characteristics and thus fail to meet the requirements of the end users. For example, gears manufactured by hobbing and shaping have tool marks and scallops on the gear tooth surface. Post-manufacturing heat treatment to improve gear hardness also adversely affects the surface characteristics of the gears. Therefore, a proper gear-finishing process becomes necessary to ensure better surface characteristics of a gear to eliminate various defects and sub-surface damages induced during gear manufacturing and heat treatment processes. Karpuschewski et al. (2008) mentioned that the gear-finishing process should fulfill two major goals: (i) improvement in surface quality and reduction in form errors to minimize the running noise; and (ii) flank modifications and improving surface integrity to maximize the load-carrying capacity. Fig. 1.5 presents means of achieving these goals. Fig. 1.6 shows the surface characteristics of a gear that can be improved by an appropriate gear finishing process. It can be concluded from these figures that improvement in surface quality and surface integrity and reduction in form errors of a gear can be achieved by selecting an appropriate gear-finishing process and surface properties-enhancing process.

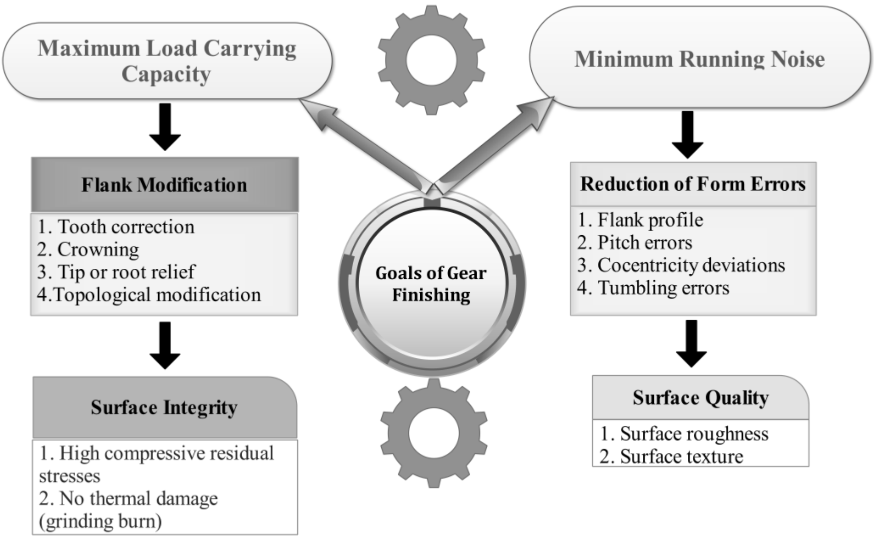


Fig. 1.5: Goals of finishing a gear and means of achieving them.

The most commonly used conventional processes for gear finishing are gear shaving, gear burnishing, gear honing, gear grinding and gear lapping. These processes have limited capabilities and suffer from their inherent limitations. Table 1.5 summarizes the capabilities, applications, advantages and limitations of these processes and the following paragraphs briefly describe them.

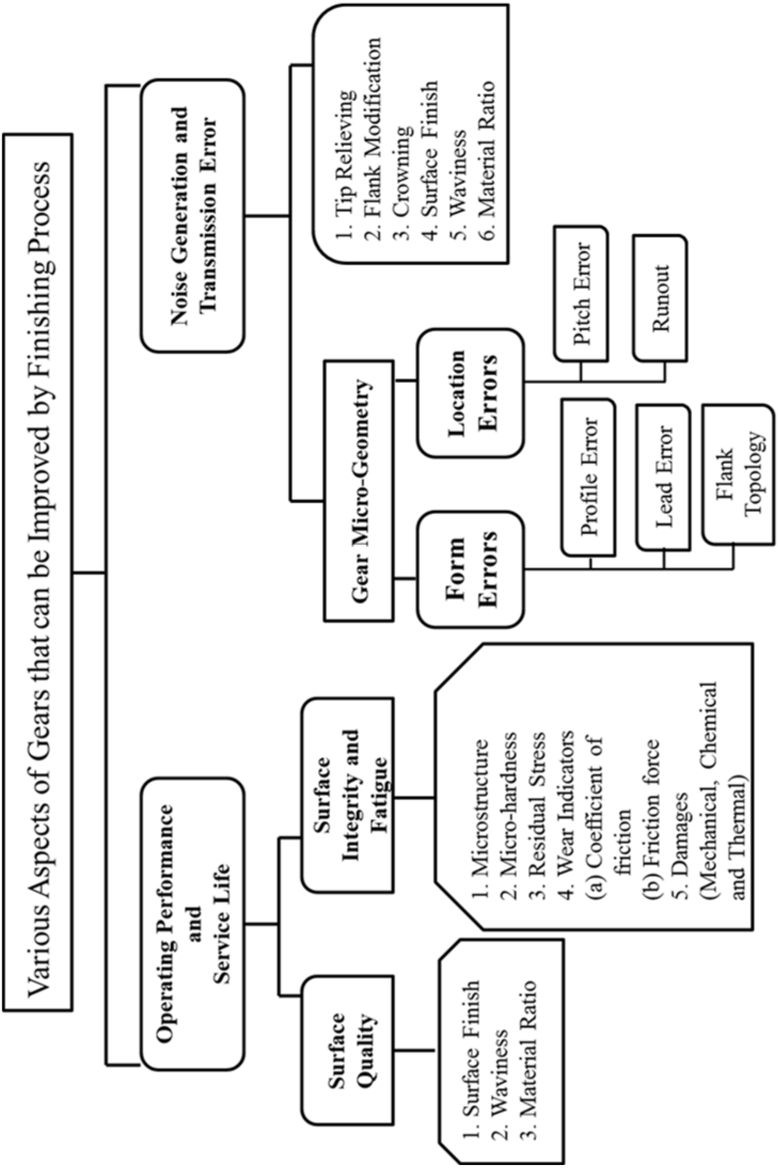


Fig. 1.6: Surface characteristics of a gear that can be improved by finishing process (Reported from Pathak et al. (2016) with permission; Copyright 2016, Springer)

Table 1.5: Summary of conventional finishing processes of gears.

Process	Capabilities	Limitations	Applications
Gear Shaving	• Corrects error in index, helical angle, tooth profile, and eccentricity. • Improves tooth surface smoothness. • Reduces gear noise.	• Can be used for gears *up to 40 Rockwell C scale or* unhardened.	• For finishing of spur, helical and worm and worm wheels.
Gear Burnishing	• Improves surface integrity and fatigue life of the gears. • Faster than other conventional gear finishing methods.	• Some undesirable effects such as localized surface stresses and non-uniform surface characteristics are produced due to cold working. • Can be used only for soft and unhardened gears only.	• For finishing helical gears.
Gear Honing	• It improves noise characteristics of the gears. • It produces a cross-hatch lay pattern on finished gear teeth surface, which improves lubricating oil retention. It also improves concentricity. • Correct the distortion after heat treatment.	• Can be used only for unhardened gears only. • Limited life of honing tool. • Slow process.	• For finishing of spur, helical and bevel gears.

Gear Grinding	• It is a very accurate and frequently used gear finishing process. • It finishes gears having hardness value up to 92 HRC. • It can do profile modification. • It improves the accuracy of gears.	• The thermal damage may lead to grinding burn on the gear surface. • Generates transverse grind lines on the gear face, which increases noise and vibrations of a gear. • Redressing of grinding wheels affect form accuracy of a gear. • Cost of grinding machine is very high and operation is complicated as it requires skilled machine operator. • Take long time in form grinding. • Grinding cannot modify some special gears such as an inner gear, multi-joint gears, very large gears.	• Generally used to finish tooth profile of different types of gears made of hard materials and gears that have been hardened after their manufacturing. • For finishing of spur, helical and bevel gears.
Gear Lapping	• It corrects minute distortions caused by heat-treatment, errors in involute profile, helix angle, spacing, and eccentricity in the hardened gears. • Gear tooth contact improves by lapping.	• Longer lapping cycles affect form accuracy adversely. • Only mating gears are lapped in a pair and they cannot be interchanged.	• For finishing of spur, helical, bevel gears, spiral bevel and hypoid gears. • Usually employed on those gears that have been shaved and hardened.

1.4.1 Gear Shaving

Gear shaving removes a small amount of material from the workpiece gear to correct errors in its profile, pitch, helix angle and eccentricity and improves the surface finish of the gear by using a specially shaped shaving cutter, which is similar to a helical gear having serrated cutting edges. Gear shaving is basically a low pressure, free-cutting process used for spur gears, helical gears and worm and worm wheels. It also removes the cutter marks, waviness and surface irregularities induced by the gear manufacturing process. However, it can only finish the gear with a hardness up to 40 HRC. Also, the accuracy of the gear depends on the accuracy of the shaving cutter. Cutter design is complex and the cutter is costly. It can be used for gears up to a diameter of 40 mm and a module of 4 mm only. Fig. 1.7 presents the schematic of the working principle of transverse shaving processes. The shaving cutter and workpiece gear are pressed to make proper meshing contact and the center distance between the cutter and workpiece gear is reduced incrementally. The shaving cutter rotates in a tight mesh with the workpiece gear either in parallel or a crossed axes arrangement. The meshing between the cutter and workpiece gear is flexible enough to obtain any desired value of cross-axes angle. The rotary motion between the workpiece gear and shaving cutter is performed in both directions (i.e. clockwise and anticlockwise) during the finishing cycle and material removal takes place in the form of hair-like chip. Workpiece gear is reciprocated parallel to its axes across the face of the cutter and fed into the cutter with each stroke of the table. Cutting action in gear shaving includes fine cutting and finishing caused by a land shaving cutter.

1.4.2 Gear Burnishing

Gear burnishing is used to improve the surface finish and accuracy of the gears after cutting and prior to hardening. Unhardened workpiece gear is rolled with one or several burnishing gears having teeth that are hard, smooth and highly accurate in the presence of ample lubricant (but no abrasive), as shown in Fig. 1.8. Pressure exerted by the burnishing gear on flank surfaces of the workpiece gear leads to a work-hardening effect and smooths out all the irregularities. This process is applicable only for unhardened gears not requiring high accuracy.

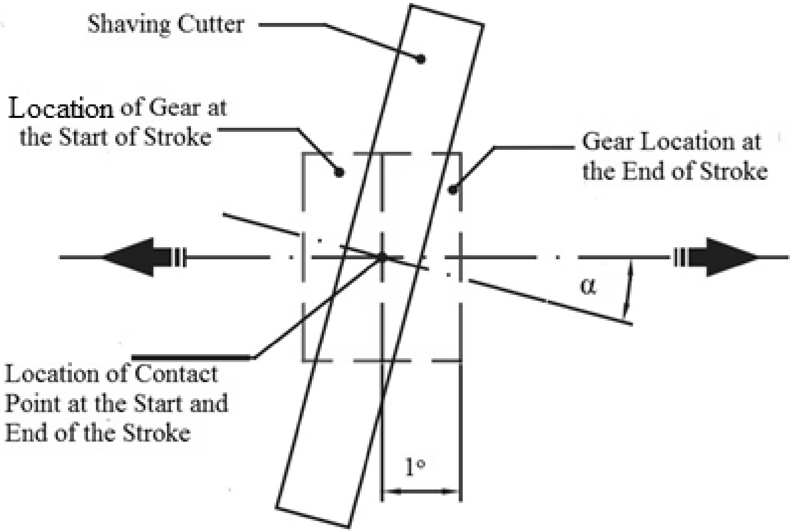


Fig. 1.7: Schematic of transverse gear shaving process.

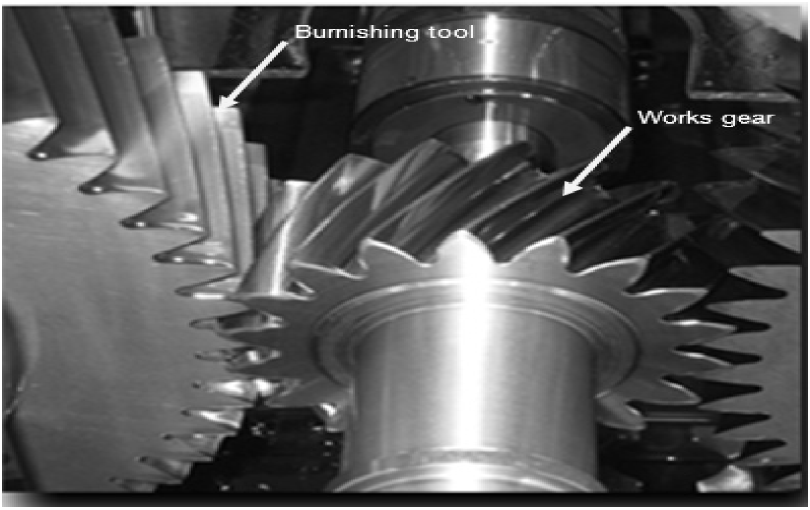


Fig. 1.8: Illustration of gear burnishing process.

1.4.3 Gear Honing

Gear honing is a hardened gear-finishing process that uses an abrasive-impregnated helical gear-shaped tool that runs in tight mesh with the hardened workpiece gear in a cross-axes relationship. Two basic methods are used to hone the gear teeth. One is the zero-backlash method and the other is called the constant-pressure method. The *zero-backlash method* is used for hardened gears made within commercial tolerance specifications while the *constant pressure method* is used to hone the gear teeth on hardened gears produced to dimensions outside commercial tolerance ranges. Depending on the relative position of the honing and workpiece gears, gear honing can be performed either as (i) **external honing:** In this process, honing and workpiece gears mesh with each other in a cross-axis arrangement with constant center distance. Gear teeth are finished from root to the tip and the direction of rotation of the honing gear is reversed for finishing the second flank, or (ii) **Internal honing:** In this process, a large-size internal helical gear made of a ceramic material is used as a honing tool that has cross-axis meshing with the workpiece gear held between the centers of the honing machine, as shown in Fig. 1.9. Axes of the honing gear can be varied to match the required crossed-axis angle meshing arrangement with workpiece gear. The gear honing machine has the provision to traverse back and forth along the workpiece gear axis to finish a gear with a large face width. The material of the honing gear must have the capability to yield the required gear profile as well as hold its shape under pressure. Generally, it is a mixture of plastic resins (polyurethane and epoxy matrix) and abrasive grains and is formed in a precision mold. The abrasives are held together by a bond which can be a vitrified, resinoid or metallic type. The bond must be strong enough to hold the abrasive grains but should not be so hard that it rubs workpiece gear and deteriorates its quality rather than improves it. Abrasive grain size generally depends on the desired MRR and surface finish. Generally, it varies from 60 to 500 mesh number. The type of honing gear depends on the workpiece gear material, finishing method, application requirement, and available machine capacities. The size of the honing gear ranges from 3.5” (for internal gears) to 14” while face width ranges from 0.5” to 2” (Jain and Petare, 2016).

Functional characteristics of the gears such as geometric accuracy, dimensional accuracy, roughness, lay pattern, minor corrections in tooth irregularities, noise and wear characteristics and integrity of gears can be improved by gear honing. However, the honing process suffers from the limited life of the honing tool, low productivity, incapability of finishing a hardened workpiece and the possibility of mechanical damage (i.e. micro-cracks, hardness alternation and plastic deformation) to the workpiece material. Conventional honing oil is used as a coolant, lubricant and to flush away the wear debris. The amount of material removed from the workpiece gear ranges from 13 to 50 μm.

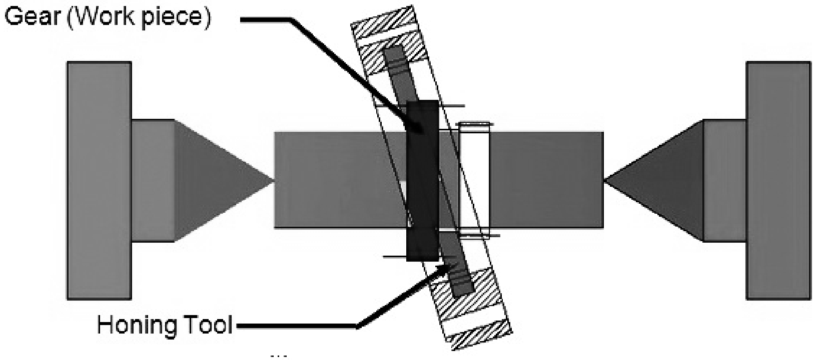


Fig. 1.9: Schematic of internal honing of an external gear.

1.4.4 Gear Lapping

Gear lapping finishes the mating gears in a conjugate pair only and can rectify only minute deviations from the desired gear tooth profile. Fig. 1.10 shows its schematic in which the workpiece gear is run under load in mesh with lapping gear made of a softer material compared to that of workpiece gear. Lapping compound consisting of abrasive particles and oil is made to flow in the form of a paste between the mating pairs of the teeth. One of the mating members (either gear or lapping tool) is reciprocated axially along with rotary motion. Before starting the lapping process, both gears are ground with a hand grinder to remove nicks and burrs. In this process, the pinion (smaller gear) is used as the driver and the larger gear as the driven member. It is a slow process and if performed for a longer duration, it affects the accuracy of the gear teeth profile in a detrimental manner. Gear lapping is used to improve the surface finish of a gear. Low noise between the mating gears is the criterion for successfully lapping. Lapping being a mating process, no stock clearance allowance is provided on the workpiece gear.

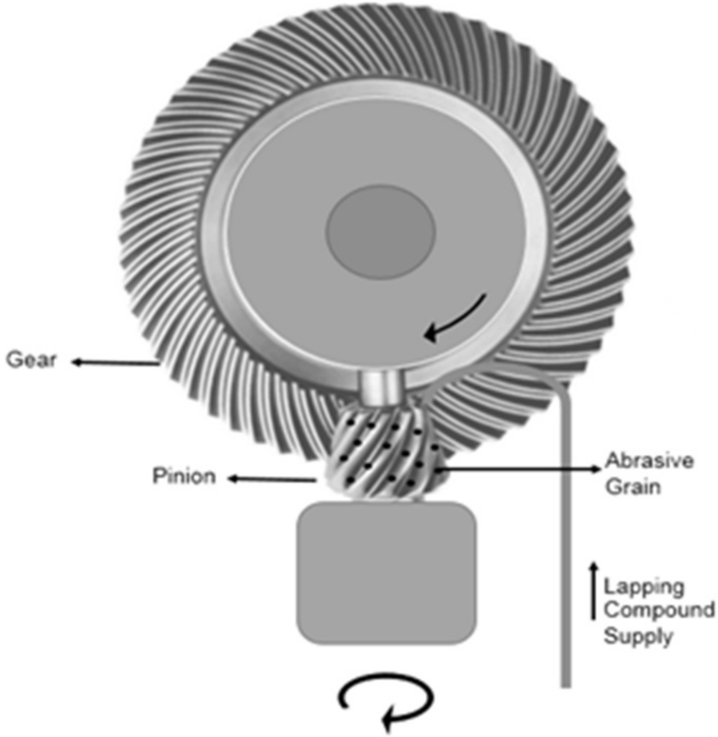


Fig. 1.10: Schematic of gear lapping process.

1.4.5 Gear Grinding

Heat treatment processes have the tendency to thermally distort the gears thus deteriorating their tooth accuracy. This necessitates the hard finishing of the gear teeth. Gear grinding is an effective means of finishing the hard and hardened gears (having hardness 40 HRC and above). It uses a properly formed and dressed grinding wheel that finishes the gear teeth flanks by the abrading action of the fine abrasive wheel. According to the shape of the grinding wheel, it can be classified into two types (i) ***form or non-generative grinding***, which uses a grinding wheel shaped according to geometry of the workpiece gear tooth; (ii) ***generative grinding***, which uses a generic-shaped grinding wheel to finish a range of workpiece gear geometry by providing different motions to the grinding wheel and using different shapes of it. The different shapes of the grinding wheel can be the