The Enhancement of Gear Quality through the Abrasive Flow Finishing Process

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Anand Petare, Neelesh Kumar Jain
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PREFACE

A gear is a modified form of a wheel. Globally more than 10 billion gears of different types are bought per year. This makes the manufacturing and finishing of gears very important in terms of technological, environmental, and economical aspects. Continuous research and innovations are required to develop technically superior, environment-friendly, productive, and affordable processes for the manufacturing and finishing of different types of gears made of wide-ranging materials. The abrasive flow finishing (AFF) process is such an advanced finishing process as it fulfills most of the requirements of a modern gear finishing process, but its potential for gear finishing has not yet been fully exploited.

The objective of this book is to provide details of the extensive work done to the AFF process for the high quality finishing of cylindrical (i.e. spur) gears and conical (i.e. straight bevel) gears. It consists of ten chapters. The first chapter introduces different aspects of the abrasive flow finishing (AFF) process, including its types, different parameters, advantages, limitations, and some typical applications. Chapter 2 introduces gears, their materials, the manufacturing process and quality evaluation parameters, traditional gear finishing processes, and a summary of their limitations. Chapter 3 presents a comprehensive review of past work on the finishing of different types of gears by the AFF process, the use of laser texturing, the effect of gear finishing on noise and vibration reduction, the existing gaps, and the objectives of the present work and the methodology adopted to meet them. Chapter 4 describes the development of the AFF machine for the AFF process, the fixtures for finishing and holding spur and straight bevel gears, and the details of the selected materials for finishing the spur and straight bevel gears as well as their specifications. Chapter 5 details the design, planning, and conduct of experimental investigations in different stages along with an evaluation and characterization of the surface roughness, microgeometry, surface morphology, microhardness, and wear indicating the parameters of spur and straight bevel gears finished by the AFF process. Chapter 6 presents the obtained results, their analyses, and conclusions from different stages of the experiments. Chapter 7 presents details of the optimization of the AFF process parameters and experimental validations of the optimization results. Chapter 8 describes the laser texturing of spur and straight bevel gears and a comparative study of AFF of the untextured and laser-textured gears in terms of microgeometry error, surface roughness, surface morphology, wear characteristics, and microhardness. Chapter 9 presents an evaluation and analysis of the functional performance parameters and noise and vibration characteristics of the gears finished by the AFF along with their comparison with unfinished gears. Chapter 10 concludes this book by presenting significant achievements and conclusions, and directions for future research.

It is expected that this book will be of great help to the manufacturers and users of different types of gears who are looking for a better gear finishing process.

Anand Petare
Neelesh Kumar Jain
I A Palani

NOMENCLATURE

C_{av}	Volumetric concentration of the abrasive particles in the AFF medium (%)
d_a	Diameter of the abrasive particles (μm)
fi	Tooth-to-tooth composite error (μm)
ff_a	Profile form error (μm)
ff_β	Lead form error (μm)
fh_a	Profile angle error (μm)
fh_β	Lead angle error (μm)
F	Applied normal load (N)
F_a	Total profile error (μm)
F_β	Total lead error (μm)
F_i	Total composite error (μm)
F_p	Total pitch error (μm)
F_r	Radial runout determined by the microgeometry error measurement (μm)
F_{rf}	Radial runout determined by the double flank roll testing (μm)
k_i	Specific wear rate (mm^3/Nm)
M_a	Abrasive particles size (mesh) $\left[M_a = \frac{15.24}{d_a\ (in\ mm)}\right]$
ΔN	Change in noise level (dBA)
O_c	Volumetric concentration of silicone oil in the AFF medium (%)
P	Extrusion pressure in the AFF process (MPa)
PRF_a	Percentage reduction in total profile error (%)
PRF_β	Percentage reduction in total lead error (%)
PRf_p	Percentage reduction in single pitch error (%)
PRf_u	Percentage reduction in adjacent pitch error (%)
PRF_p	Percentage reduction in total pitch error (%)
PRF_r	Percentage reduction in radial runout (%)
PRR_a	Percentage reduction in average surface roughness (%)
PRR_{max}	Percentage reduction in maximum surface roughness (%)
R_a	Average surface roughness value (μm)
ΔR_a	Change in average surface roughness value (μm)
R_{max}	Maximum surface roughness value (μm)

ΔR_{max}	Change in maximum surface roughness value (μm)
S	Total sliding distance in the wear test (m)
t	Finishing time in the AFF process (Minutes)
ΔV	Change in vibration level (mm/sec^2)
η	Viscosity of the AFF medium (kPa.s)
m_i	Mass loss during the wear test (mg)
ρ	Density of the gear material (kg/mm^3)

ACRONYMS

AFF	Abrasive Flow Finishing
AGMA	American Gear Manufacturers Association
ANOVA	Analysis of Variance
BBD	Box-Behnken Design
CCD	Central Composite Design
CNC	Computer Numeral Control
COF	Coefficient of Sliding Friction
DFA	Desirability Function Analysis
DIN	Deutsches Institut für Normung
DOE	Design of Experiments
DOF	Degree of Freedom
HRB	Rockwell Hardness at B Scale
HV	Vickers Hardness Number
LF	Left Flank
LTSBG	Laser Textured Straight Bevel Gear
LTSG	Laser Textured Spur Gear
MRR	Material Removal Rate
RF	Right Flank
RSM	Response Surface Methodology
SBG	Straight Bevel Gear
SG	Spur Gear
SEM	Scanning Electron Microscope
UAAFF	Ultrasonic Assisted Abrasive Flow Finishing
USG	Untextured Spur Gear
USBG	Untextured Straight Bevel Gear
WSEM	Wire Spark Erosion Machining

CHAPTER ONE

OVERVIEW OF ABRASIVE FLOW FINISHING

Abrasive flow finishing (AFF) is an advanced nano-finishing process developed by Extrude Hone Corporation (USA) in 1960. It is meant for finishing inaccessible and restricted areas in components, the simultaneous finishing of a large number of holes, the radiusing and deburring of complicated components, and the removal of the recast layer. Figure 1.1 depicts the working principle of the AFF process schematically. It uses hydraulically or mechanically controlled movements of a semi-solid, self-deformable, and pliable finishing medium in the form of a putty through the workpiece itself or a flow path formed between the workpiece and its holding fixture (Rhodes, 1991).

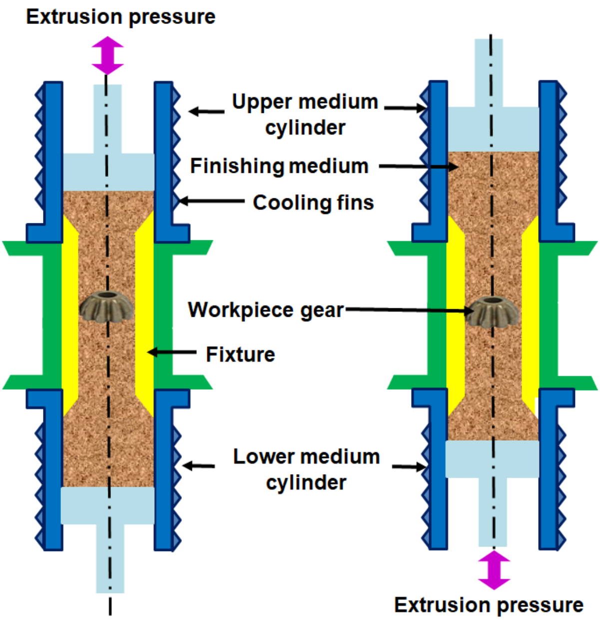

Fig. 1.1: Schematic of working principle of the abrasive flow finishing (AFF) process

A typical machine for the AFF process consists of four main subsystems, namely the (i) power supply unit to provide the required extrusion pressure hydraulically, pneumatically, or mechanically for the controlled movement of the AFF medium, (ii) supporting structure, (iii) workpiece fixture, and (iv) AFF medium. The power supply unit consists of hydraulic or pneumatic cylinders, cylinders containing the AFF medium, a power supply unit along with the control panel, direction control valves, a pressure regulator to set the desired pressure, and a pressure gauge. The supporting structure comprises plates and rods for supporting the hydraulic or pneumatic cylinders, cylinders containing the AFF medium, workpiece fixture, limit switches to set the stroke length, and a stroke counter. The workpiece fixture is designed according to the geometry and size of the component and the area to be finished. It can also be designed to finish the multiple components in a single setting of the AFF machine. It serves two functions: (a) to hold the workpiece tightly between the AFF medium-containing cylinders so it does not move while being finished at high extrusion pressure, and (b) to direct the flow of the AFF medium to those parts of the workpiece where finishing is required and restrict its flow where finishing is not required. Materials such as hardened steel, Teflon, Nylon, and Metlon can be used to make the workpiece fixture. The finishing medium used in the AFF process generally contains a uniform mixture of viscoelastic polymer, abrasive particles whose type and size depend on the type and hardness of the workpiece material and its finishing requirements, and the blending oil, which is used to maintain the desired viscosity of the AFF medium.

1.1 Types of AFF Process

The AFF process can be classified into the following four types according to the flow of the finishing medium and arrangements required for it:

- **One-way AFF:** In the one-way AFF process, the AFF medium is extruded from one end of the workpiece and collected at other end after one finishing cycle and has to be reinserted again for the next finishing cycle, as shown in the Fig. 1.2a. Although the process takes a very long time to finish a component and causes more wastage of the finishing medium, it maintains its freshness and thus its chemical composition and rheological properties do not change.

- **Two-way AFF:** The AFF medium in the two-way AFF process is moved back and forth continuously between two medium-containing cylinders, with the workpiece and its fixture sandwiched between them, as depicted in the Fig. 1.2b. The machine is heavier and costlier, and design of the fixtures for this process is also complicated. The AFF medium remains contained within the medium-containing cylinders until there is a change in the chemical composition and rheological properties of the AFF medium. There is a problem with leakage of the AFF medium.
- **Multi-way AFF:** The AFF medium is moved back and forth between four medium-containing cylinders in the multi-flow AFF process, as illustrated in the Fig. 1.2c. Two fixtures containing two workpieces are placed parallel to each other and an arrangement is made to transfer the AFF medium in cross-direction. Its machine is the heaviest and most complicated because it requires special arrangements to sequence the hydraulic operations.
- **Orbital AFF**: The AFF medium is moved back and forth between two hydraulically operated cylinders containing the AFF medium through a displacer whose shape is complementary to the workpiece geometry, as shown in the Fig.1.2d. Orbital vibrations are provided to the workpiece in the transverse direction. This process requires manufacturing the displacer, and its machine can provide orbital vibrations of the desired frequency and amplitude.

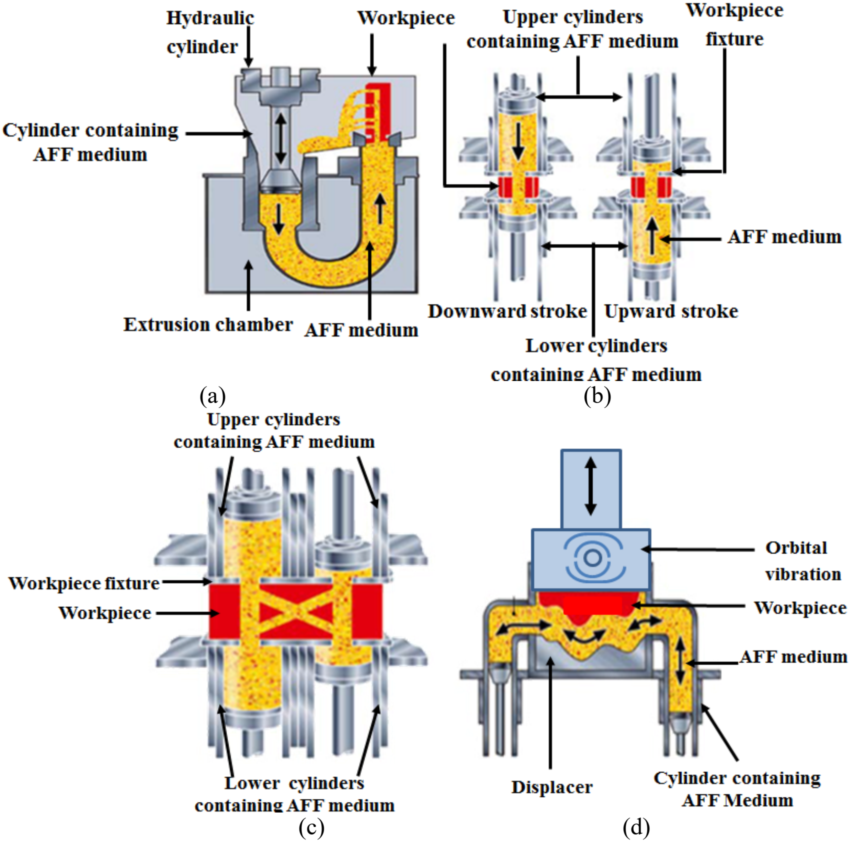

Fig. 1.2: Schematic views of four types of the AFF process: (a) one-way AFF; (b) two-way AFF; (c) multi-way AFF; and (d) orbital AFF (Petare and Jain, 2018) Reprinted with permission from Springer © 2018.

1.2 Parameters of the AFF Process

Required surface finish and material removal rate can be achieved by selecting a proper parametric combination of the AFF processes. They can be classified into three groups, namely, parameters associated with the AFF medium, AFF machine, and the workpiece (Jain, 2009).

1.2.1 Parameters Associated with the AFF Medium

Parameters associated with the AFF medium that affect the performance of the AFF process include type, size, and concentration of the abrasive particles, type of visco-elastic polymer, type and amount of the blending oil, and viscosity, temperature, and functional life of the AFF medium.

- **Type, size, and concentration of the abrasive particles:** The selection of the size and type of the abrasive used in the AFF medium depends on the type and finishing requirements of the workpiece material. Commonly used abrasives include alumina (Al_2O_3), silicon carbide (SiC), cubic boron carbide (CBN), diamond, and a mixture of these abrasives. Alumina is generally used for the softer workpiece materials and other abrasives for the harder workpiece materials. Fine abrasive particles are mostly preferred when a high-quality surface finish is required for the components whereas coarse abrasive particles are generally used for deburring and radiusing applications. An increase in MRR and surface roughness has been observed with an increase in abrasive particle size because higher abrasive particle sizes cause more indentation depth in the workpiece (Williams and Rajurkar, 1992). The volumetric concentration of abrasive particles is their % volume in the total volume of the AFF medium. The ratio of volume of abrasive particles to volume of viscoelastic polymer (or silly putty) can vary from 1:4 to 4:1; however, it has been suggested that a 1:1 ratio achieves a better surface finish (Perry, 1985). A higher concentration of abrasive particles increases the chance of jamming the cylinders containing the AFF medium. An optimum value of abrasive concentration exists because surface roughness decreases and MRR increases with an increase in abrasive concentration due to more abrasive particles being available for finishing the workpiece surface. However, after the optimum value, this trend reverses because the AFF medium tends to become rigid, thus losing its self-deformable nature (Sankar et al., 2009).
- **Type and concentration of the blending oil:** Blending oil is used to ensure the proper mixing of the visco-elastic polymer with the abrasive particles to form a bond between them and impart the

required viscosity to the AFF medium. Silicone oil, turpentine oil, and hydrocarbon-based oils are commonly used. An excessive amount of blending oil makes the AFF medium behave like a liquid and reduces its finishing capability, whereas too little imparts a high rigidity to the AFF medium, making it behave like a solid, which increases the chances of choking the medium-containing cylinders.

- **Viscosity of AFF medium:** The viscosity of the AFF medium depends on the type of viscoelastic polymer and the amount of blending oil used. A higher viscosity of the AFF medium increases the bonding strength between the abrasive particles and the polymer, causing more material removal from the workpiece and producing a uniform surface. A lower viscosity of the AFF medium reduces the bonding between the polymer and abrasive particles, which causes a rotation of the abrasive particles on the workpiece surface rather than sliding thus reducing MRR and increasing surface roughness. It is used for radiusing and deburring applications. For a given volume of AFF medium, viscosity increases with an increase in the concentration of the abrasive particles (Rajeshwar et al., 1994).
- **Temperature of the AFF medium**: Past research has revealed that the temperature of the AFF medium has a significant influence on its rheological properties (i.e. viscosity, viscoelasticity, thixotropy, etc.) and that it can increase by 30–70°C (Agrawal et al., 2005). The viscosity of the AFF medium decreases with an increase in its temperature due to a reduction in the bonding between the abrasive particles and viscoelastic polymer. This increases the settling tendency of the abrasive particles at the bottom of the medium-containing cylinder. Therefore, the temperature of the AFF medium should not be allowed to go beyond 100°C (Hull et al., 1992).
- **Preparation method of the AFF medium:** The AFF medium can be prepared by different methods such as kneading, rotary mixing, extrusion, and in the AFF machine itself without using the workpiece. The selected method should ensure a uniform mixing of the constituents of the AFF medium.
- **Functional life of the AFF medium:** The AFF medium is a consumable and its lifetime is typically about 250 hours, but the

actual value depends on the shape, size, and amount of finishing to be done (Przyklenk, 1986).

1.2.2 Parameters Associated with the AFF Machine

Parameters associated with the AFF machine include extrusion pressure, volume of the AFF medium (which is determined by the diameter and stroke length of the medium-containing cylinders), flow rate of the AFF medium, and the number of cycles or finishing time.

- **Extrusion pressure:** It is the summation of the force per unit contact area used in overcoming the friction between the AFF medium-containing cylinder and its piston and the force imparted on the AFF medium per unit area. It can be provided by a hydraulic, pneumatic, or mechanical power unit. Literature reveals that its value varies from 0.7 to 20 MPa (Jain and Adsul, 2000). An increase in the extrusion pressure increases the material removal rate (MRR), compressive stress on the AFF medium, and decreases average surface roughness (R_a) value (Williams and Rajurkar, 1992).
- **Volume of the AFF medium:** It is the volume of the AFF medium filled in the medium-containing cylinder and is determined by the cylinder's diameter and stroke length. A larger stroke length produces a larger slug length, which increases the abrasive action and MRR (Cheema et al., 2012).
- **Flow rate of the AFF Medium:** It is the volume of the AFF medium flowing per unit time. It depends on the viscosity of the AFF medium and the extrusion pressure.
- **Number of cycles or finishing duration:** One cycle of the AFF process consists of one upward stroke from the reference position and downward stroke back to the reference position by the piston of the medium-containing cylinder. It is a decisive factor to achieve the required surface finish. Its value depends on the desired value of surface roughness of the workpiece. Surface roughness of the workpiece decreases asymptotically with an increase in the finishing duration.

1.2.3 Parameters Associated with the Workpiece

Important parameters associated with the workpiece include the type and mechanical properties (such as ductility and hardness) of the workpiece material, type of manufacturing process used to make the workpiece, and initial surface condition.

- **Type and mechanical properties of the workpiece material:** The AFF process can be used for finishing both metallic (both ferrous and non-ferrous) and non-metallic materials (i.e. ceramics, composites, additive manufactured products). The ductility and hardness of the workpiece material significantly affect the finishing results and performance of the AFF process. Past studies have shown that finishing softer and more ductile materials by the AFF gives more MRR but a poorer surface finish than finishing the harder materials. This is due to a deeper indentation by the abrasive particles in softer materials than in the harder materials (Rhodes, 1991).
- **Type of manufacturing process used to make the workpiece:** AFF can be used to nano-finish milled, turned, ground, and wire-spark-erosion-machined (WSEMed) components (Loveless et al., 1994). It can achieve a very good improvement in the surface finish with the removal of a very small amount of material from the workpiece, and the finishing results are reliable, uniform, repeatable, predictable, and accurate.
- **Initial surface condition:** The initial condition of the workpiece surface significantly affects the finishing results by the AFF process. More variations in surface roughness produce more MRR but less improvement in the surface finish because at the start of the AFF process, the abrasive particles come in contact with the higher surface peaks and flatten them. However, after some finishing cycles, the flattening of a greater number of surface peaks takes place simultaneously. Loveless et. al (1994) compared the mechanism of material removal in the finishing of WSEMed, turned, milled, and ground surfaces by the AFF process and concluded that the WSEMed surface yields the best results because it has surface peaks with less height, micro-cracks, and loosely attached white layers.

1.3 Advantages of the AFF Process

The following are the advantages of the AFF process:

- It gives average surface roughness values as small as 50 nm with a dimensional tolerance as low as ± 5 μm. The thickness of the material removed is in the range of 1 to 10 μm.
- Multiple holes can be finished simultaneously in a single setup of the AFF process in minimum time. A minimum limit on the hole size that can be finished /deburred properly is 0.22 mm in diameter, and the largest size that has been finished is around 1000 mm in diameter.
- Finishing multiple parts simultaneously results in uniformity, repeatability, and predictability. Automatic AFF machines can finish thousands of parts per day, and the labor costs are reduced significantly by reducing manual handwork.
- It offers flexibility for changes in material, geometry, and dimensions of the workpiece, type of the AFF medium and abrasives, and the AFF process parameters, thus enabling finishing a variety of parts on the same setup just by changing the fixtures for holding the workpiece. It gives a general-purpose finishing solution for the mass production.
- The AFF medium can be selected according to the finishing requirements and the economic aspects.

1.4 Limitations of the AFF Process

The following are the limitations of the AFF process:

- Unable to improve surface irregularities such as out-of-roundness, tapered holes, blind holes, deep scratches, large bumps, cavities, etc.
- The material removal rate in the AFF process is very small hence it is not applicable for mass-scale material removal purposes.
- Uncertainty about the distribution of the abrasive particles in the AFF medium and difficulty controlling the rheological properties of the AFF medium.
- The design of fixtures changes every time according to the geometry of the part, and the development of a suitable restriction

and tooling to obtain the desired finish on the selected areas is a major challenge.

1.5 Applications of the AFF Process

The AFF process finds wide applications for finishing the various components used in different fields. Some major applications are listed below:

- Finishing of different components used in the aerospace, automotive, diesel, and turbine engine industries, i.e. deburring of aircraft valve bodies and spools, fuel spray nozzles, fuel control bodies, airfoil surfaces of impellers, common rail pipe fuel system of a diesel engine, outer rotor surface of the cycloidal pump, etc.
- Finishing of the fluid handling components of the food processing systems and the components manufactured by additive layer manufacturing processes.
- Aerospace applications include the removal of the thermal recast layer in the cooling holes of blades and disks, deburring of the fuel spray nozzles, and polishing cast surfaces of blades, compressor wheels, and impellers.
- Radiusing and deburring air-cooling holes of turbine disk and holes of combustion liner.
- Materials ranging from soft aluminum to hard nickel alloys, ceramics, and carbides can be successfully finished by the AFF process.
- Surface integrity problems such as residual stresses, metallurgical transformations, plastic deformations, heat-affected zones, recrystallizations, tearing, and cracking can be reduced or avoided.

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CHAPTER TWO

INTRODUCTION TO GEARS

The gear is a mechanical component used to transmit motion or power between the two shafts through successive engagements of teeth cut on its periphery. It constitutes an economical means to transmit motion and power with high accuracy. Different types of gears are used in different industries, scientific organizations, and commercial and domestic applications, including automobiles (i.e. cars, trucks, tractors, motorcycles, scooters, etc.), the aerospace industry (i.e. high-speed aircraft engines), the marine industry (i.e. high power high-speed marine engines, navy fighting ships), control systems (i.e. gun, helicopter, tanks, radar applications), earthmoving equipment, home appliances (i.e. washing machine, food mixtures, fans, etc.), toys, gadgets, micro and nanodevices, and the oil and gas industry (i.e. oil platforms, pumping stations, drilling sites, refineries, and power stations). Gears can be classified according to the following criteria (Davis, 2005; Townsend, 2011; Radzevich, 2016):

- **Relative position of the axes of the shafts on which gears are mounted:** Gears mounted on the parallel shafts are manufactured from the cylindrical blanks, therefore they are known as *cylindrical gears*. Spur, single helical, double helical, and herringbone gears belong to this category. Gears mounted on the intersecting shafts are manufactured from the frustum of conical blanks so they are referred to as *conical gears*. Straight bevel, spiral bevel, zero bevel, miter gear, and face gear or crown wheel are examples of conical gears. Gears mounted on non-parallel and non-intersecting axes are called *skew shaft gears*. Rack and pinion, crossed axes helical gears, worm and worm wheel, cylindrical worm gears, single enveloping worm gears, double enveloping worm gears, hypoid gears, spiroid, and helicon gears belong to this category.

- **Shape of the gear:** Circular or non-circular gears. triangular, square, rectangular, pentagonal, elliptical, scroll, lobbed, segmented, and multiple sector gears are some examples of the non-circular gears. They are mostly used where variable velocity ratio, non-uniform motion, interrupted motion with dwell time, and special motion are desired.
- **Size of major diameter:** Gears can be classified as micro-sized (0.1 to 1 mm), meso-sized (1 to 10 mm), and macro-sized (above 10 mm).
- **Location of gear teeth:** Can be classified as external or internal type gears.
- **Profile of gear teeth:** Can be classified as involute, cycloidal, or mixed profile gears.
- **Shape of gear teeth:** Can be classified as straight, inclined, or curved teeth gears.
- **Peripheral velocity:** Can be classified as low velocity (less than 3 m/s) gears, medium velocity (3 to 15 m/s) gears, or high velocity (above 15 m/s) gears.
- **Form of gear profile:** Can be classified as standard gears or profile shifted gears.
- **Pressure angle:** Can be classified as constant pressure angle gears or variable pressure angle gears.
- **Function:** Can be classified as motion transfer gears, power transfer gears, and precision gears for scientific applications.

Figure 2.1 depicts photographs of different types of gears.

Fig. 2.1: Photographs of different types of gears

2.1 Materials for Gears

The selection of an appropriate material for a gear is an important factor to achieve its desired performance, strength, resistance to wear, impact and fatigue, and service life. It is based on the required shape, size, application, transmission, tolerances, surface finish, and economic aspects. Both metallic and non-metallic materials can be used to manufacture the gears mentioned in table 2.1. Metallic materials can be further classified as ferrous and non-ferrous. Ferrous gear materials include plain carbon steel, cast steel, tool steel, stainless steel, and cast iron whereas copper and its alloys (brass and bronze) and the alloys based on titanium, nickel, aluminum, and magnesium are the commonly used non-ferrous gear materials. Nylon, Teflon, Metlon, Phenolic, Derlin, and olypropylene are the commonly used non-metallic gear materials.

Table 2.1: Different types of gear materials

Metallic		Non-metallic (Plastics)
Ferrous	**Non-ferrous**	
Cast iron	Aluminum alloys	Nylon
Cast steel	Copper alloys (Brass and bronze)	Teflon
Plain carbon steel	Titanium alloys	Derlin
Stainless steel	Nickel alloys	Phenolic
Tool steel	Magnesium alloys	Metlon
	Sintered powder	Polypropylene

2.2 Manufacturing Processes for Gears

The manufacturing processes for gears can be classified as traditional and non-traditional or advanced processes. Traditional processes are further classified according to cylindrical or conical gear manufacturing processes. The manufacturing processes for cylindrical gears are further divided into the following three categories: (i) subtractive type, i.e. gear machining processes, (ii) deformative type, i.e. gear forming processes, and (iii) accretion type. Cylindrical gear machining processes are further classified as the generative processes, which use a generic tool for cutting the gear, and the form cutting processes, which use a tool whose shape corresponds to the shape of the gap between two consecutive teeth to be cut for a particular type of gear. Conical gear manufacturing processes are classified into two categories: (i) generative, and (ii) non-generative. Non-traditional or advanced manufacturing processes for gears are further categorized into four categories, namely (i) subtractive type, i.e. spark erosion machining (SEM), μ-SEM, wire SEM (WSEM), μ-WSEM, water jet machining (WJM), abrasive water jet machining (AWJM), and laser beam machining (LBM); (ii) additive type; (iii) deformative type; and (iv) hybrid type. Table 2.2 illustrates the various manufacturing processes used for gears of each type.