Analysis and Comparison of Noise and Vibrations of Spur Gears Finished by Advanced Finishing Processes

M.Tech. Thesis

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Discipline of Mechanical Engineering

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Analysis and Comparison of Noise and Vibrations of Spur Gears Finished by Advanced Finishing Processes

A THESIS

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Candidate's Declaration

I here by certify that work which is being presented in the thesis entitled **Analysis and Comparison of Noise and Vibrations of Spur Gears Finished by Advanced Finishing Processes** in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF MECHANICAL ENGINEERING, Indian Institute of Technology Indore,** is an authentic record of my own work carried out during the time period June 2016 to July 2017 under the supervision of **Professor Neelesh Kumar Jain,** and **Dr. Anand Parey** of Discipline of Mechanical Engineering.

The matter contained in this thesis has not been submitted by me for the award of any degree from any other institute.

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This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

(Prof. Neelesh Kumar Jain) (**Dr. Anand Parey)**

Gaurav Kumar has successfully completed his M.Tech. Oral Examination held on ……………....

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Signature of the PSPC Member 2
Date:
Dr. Ram Bilas Pachori

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Dedicated

To

My Family & Friends

ABSTRACT

Gears are essential elements of various machine and equipment which are used to transmit motion and/or power mechanically and positively with and without change in the direction and/or speed of rotation by the successive engagements of teeth on their periphery.

Since gear is an essential rotating element of any machinery or equipment their gears or their assembly generally produce vibrations due to varying load on the gear teeth When these vibrations are transmitted to the other parts of the transmission system then they create unpleasant sound which is referred as noise. Noise and vibration caused by the rotation of the gears is considered a big problem. Advanced finishing processes can be used to correct manufacturing error on the tooth face and flank surfaces. Present work addresses the impact of tooth micro geometry error on the noise and vibrations. In present work noise and vibratory performance of two advanced finishing processes like Pulsed Electrochemical Honing (PECH), Abrasive Flow Finishing (AFF) and near-net shaped gear manufactured by unconventional manufacturing process (WEDM) were compared with unfinished spur gear manufactured by conventional process hobbing. Results have shown that noise and vibrations of gear depend on the quality of gear. It has been noted that gear manufactured by WEDM have very good quality and produce less noise and vibration as compare to AFF and PECH finished gear at all measured conditions.

ECH is a hybrid finishing process which combine the capabilities and advantages of electrochemical finishing (ECF) with mechanical honing and simultaneously overcome their individual limitations. Present work reports on improving the surface quality of 20MnCr5 alloy steel spur gears in terms of microgeometry. Pulse-on time of 3 ms, pulse-off time of 6 ms, finishing time of 8 minutes and voltage of 16 V produced the best surface quality gear. The average percentage improvement in total profile error (PIF_a), total lead error (PIF_b), cumulative pitch error (PIF_p) and in total runout error (PIF_r) being as 18.8% (for gear-1); 33.3% (for pionion-2); 33.2% (for gear-1); and 20.2% (for pinion-1) respectively.

Abrasive flow machining is an advanced abrasive finishing process. In the present work surface property of 20MnCr5 alloy steel spur gear reported in terms of microgeometry improvement. Extrusion pressure 5 MPa, finishing time of 15 minutes and SiC abrasive particle of mesh size 150 with 30 % weight concentration produced the best surface quality gear. The average percentage improvement in total profile error (PIF_a), total lead error (PIF_b), cumulative pitch error (PIF_p) and in total runout error (PIF_r) being as 17.5% (for gear-2); 41% (for pionion-3); 13.0% (for gear-2); and 3.8% (for gear-1) respectively.

WEDM process is a thermo-electric erosion process in which workpiece material is removed by melting and vaporization caused due to series of electric sparks occurring between a very thin wire and electrically conductive workpiece. This work exploring the wire electric discharge machining (WEDM) process for manufacturing high quality spur gear of 20MnCr5 alloy steel. Optimized parameters in the present work for less microgeometry error were (i.e. voltage 12V, pulse-on time 1μs and pulse-off time 49.5 μs). The values of total lead error (3.8 μm), cumulative pitch error (60 μm), 2^{nd} minimum value of total profile error (47 μm; gear-5 has minimum value of 45.6 μm), and 5^{th} minimum value of total runout error (83.4 μm; is gear-6 has minimum value of 50.4 μm) were obtain in the present work.

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Nomenclature

F_a	Total profile error (μm)
F_b	Total lead error (μm)
F_p	Cumulative pitch error (μm)
F_r	Total runout (μm)
α	Pressure angle of the involute profile (degree)
I	Amount of current passed in the IEG (A)
V	Applied voltage (Volts)
δ	Inter-electrode gap (mm)

Abbreviations

AMP	Advance Machining Processes
AFF	Abrasive Flow Finishing
AFM	Abrasive Flow Machining
AWJM	Abrasive Water Jet Machining
DOE	Design of Experiment
ECM	Electrochemical Machining
ECH	Electrochemical Honing
EBM	Electron Beam Machining
EDM	Electric Discharge Machining
HMP	Hybrid Machining Process
LBM	Laser Beam Machining
PECH	Pulsed Electrochemical Honing
UA-AFM	Ultrasonic Assisted Abrasive Flow Machining
WEDM	Wire Electric Discharge Machining
IEG	Inter Electrode Gap
PIF_a	Percentage Improvement in total profile error
PIF_b	Percentage Improvement in total lead error
PIF_p	Percentage Improvement in cumulative pitch error
PIF_r	Percentage Improvement in Runout

Chapter 1

Introduction

1.1 Introduction to Gears

Gears are essential elements of various machine and equipment which are used to transmit motion and/or power mechanically and positively with and without change in the direction and/or speed of rotation by the successive engagements of teeth on their periphery. They constitute an economical method for such transmission, particularly if power level and accuracy requirements are higher. Meshing of gears in a transmission system can be considered analogous to two wheels in contact at their pitch circle but offering an advantage the gear teeth preventing the slip between them. Whenever, two gears having unequal number of teeth mesh then they give mechanical advantage with both the rotational speeds and the torques of the two gears differing in a simple relationship.

1.2 Classification of Gears

Gears can be classified into many categories based on different criteria as mentioned below (**Pathak and Jain, 2017**). Figure 1.1 shows some of these gears.

1.2.1 According to position of axes of revolution

- **Cylindrical gears for parallel shafts:** Spur gears; and Helical (single, double, herringbone) gears
- **Conical gears for intersecting shafts:** Straight bevel gear; Spiral bevel gear; Zero bevel gear; Mitre gear; and Face gear or crown wheel
- **Skew shaft gears for non-parallel and non-intersecting shafts:** Hypoid gears; Crossed helical gears; and Worm and worm wheel

1.2.2 According to the location of gear teeth

- Internal gear
- External gear
- Rack and pinion

1.2.3 According to the Position of teeth on gear surface

- Gears with straight teeth
- Gears with curved teeth
- Gears with inclined teeth

1.2.4 According to the symmetry of gears

- Circular gear
- Non-circular gear

1.2.5 According to the gear tooth profile

- Involute Profile
- Cycloidal
- Non-involute

1.2.6 According to the symmetry of gears

- Circular gear
- Non-circular gear

1.2.7 According to the peripheral velocity of gears

- Low velocity gears (< 3 m/s)
- Medium velocity gears (< 3-15 m/s)
- High velocity gears (> 15 m/s)

Fig. 1.1: Different types of gears.

1.3 Cylindrical Gears

1.3.1 Spur Gears

- Spur gears have their teeth parallel to the axis and are used for transmitting power and/or motion between two parallel shafts. They are simple in construction, easy to manufacture and less costly. They have high efficiency and very good precision. They are used in high speed and high load application in all types of gear-trains for wide range of velocity ratios. They are widely used in many applications such as clocks, household gadgets, motor cycles, automobiles, railways, aircrafts, etc.

- Since spur gears have their teeth parallel to their axis therefore there is sudden engagement and disengagement between their teeth which results in more vibrations and noise particularly at higher speed and higher loads applications.
- There is no axial thrust in this type of gear.

1.3.2 Helical Gears

- Helical gears have gear teeth inclined to their axis. Therefore, for the same width, their teeth are longer than spur gears which impart them higher load carrying capacity. Their contact ratio is higher than spur gear and precision is also good. They are recommended for very high speeds and load applications. They are widely used in automotive gearboxes. Their efficiency is slightly lower than spur gears.
- They operate smoother and quieter than spur gears i.e. they result in lower noise and vibrations as compared to other type of gears at higher load and speed.
- The helix angle introduces axial thrust on the shaft in case of single helical gears but use of double helical gears eliminates this. Since, manufacturing of accurate double helical gears having opposite type of helix on each tooth is extremely difficult therefore herringbone gears which has gap between two opposite type of helix is better option.

1.4 Noise and Vibrations in Gears

Since gear is an essential rotating element of any machinery or equipment their gears or their assembly generally produce vibrations due to varying load on the gear teeth. The vibrations generated by a gear are generally amplified due to the defects and errors in their geometry and assembly and due to resonance of the structural elements of the casing or housing in which gears are enclosed for power and/or motion transmission purposes. The resonance phenomenon occurs when the speed of the gear is such that the meshing frequency or a multiple of it is equal to the natural frequency of the system on which the gears are mounted. When these vibrations are transmitted to the other parts of the transmission system then they create unpleasant sound which is referred as noise. Most of the time, gear noise is not just a problem related to gears only. It might be a system problem and gears can be exciters in the system.

Following are the main factors which contribute to generation of noise and vibrations in a gear as depicted in Fig. 1.2

- Load and speed of the gears
- Type, material and design of the gears
- Configuration of the gearbox
- Design, material and alignment of the mounting shafts and bearing

- Surface damage to the gears during their manufacturing, finishing, heat treatment and other processing
- Surface finish of flank surfaces of the gear teeth
- Errors in microgeometry of gear teeth such as errors in their form (i.e. tooth profile, lead), location errors (i.e. pitch and runout), and topography
- Accuracy in assembly of gears
- Operating conditions such as temperature, friction, running speed, type of unexpected load, type of lubrication, use of coolant, etc.
- Wear of gears

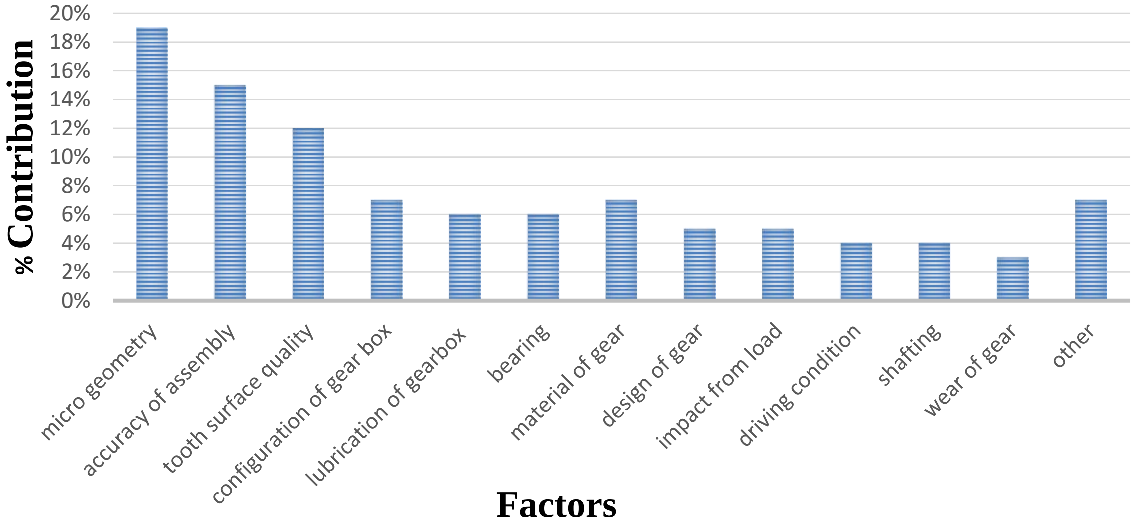


Fig. 1.2: Different factors contributing in noise and vibrations in a gear. (http://khkgears.net/gear-knowledge/introduction-to-gears/gear-noise**).**

1.5 Concept of Noise Measurement

Sound pressure or acoustic pressure is deviation of the local pressure caused by a sound wave from the atmospheric pressure. In air, sound pressure can be measured using a microphone, and in water with a hydrophone. The SI unit of sound pressure is Pascal (Pa).Whenever human beings hear a very loud noise; they experience unpleasant feelings due to pressure caused by the sound wave. Even though this pressure can be measured similar to air pressure but, in practice **acoustic pressure level** or **sound pressure level (SPL)** is a measure of the effective pressure of a sound relative to a reference value or with reference to hearing threshold. Sound pressure level, denoted $\boldsymbol{L_p}$ is defined by

$$L_p = log_e \frac{p}{p_0} (neper);\ \text{OR} = 2\, log_{10}\left(\frac{p}{p_0}\right)(Bel);\ \text{OR}\ = 20\, log_{10}\left(\frac{p}{p_0}\right)(deci\ Bel)$$

Where; p is the root mean square value of sound pressure; and p_0 is the reference pressure for sound. Commonly used reference pressure for sound in air is$p_0 = 20\,\mu Pa$;

which is often considered as the threshold for human hearing. Most of the sound level measurements are made relative to this reference i.e. for *p = 1 Pa* gives an SPL of 94 dB. In other media, such as underwater, a reference level of 1 μPa is used.

Sound intensity level (SIL) is the defined as the sound wave power per area. It is a special quantity that allows us to measure the energy of sound or to be more precise, the energy per second per one squared meter.

$$SIL = 10\,log_{10}\left(\frac{I}{I_{ref}}\right)(deci\,Bel)$$

Where, I is the sound intensity in W/m^2; I_{ref} is the reference value of the sound intensity which is typically assumed to be equal to 10^{-12} W/m^2.

While measuring SPL, distance of the measuring microphone from a sound source must be mentioned when there is only one source of sound i.e. for the measurements done at ambient or environmental conditions having some background noise then this distance need not to be quoted because no single source of source is present. Generally, distance of one metre from the sound source is a frequently used as the standard value. Because of the effects of reflected noise within a closed room, use of the anechoic chamber allows the measured sound to be comparable with sound measured in a free field environment. Figure 1.3 depicts flow chart of measurement of noise.

1.6 Concept of Vibrations Measurement

Vibration is a mechanical phenomenon in which oscillations occur about an equilibrium point. Vibrations are generally studied by monitoring displacement, velocity, or acceleration. Vibration analysis is used primarily on rotating equipment such as steam and gas turbines, pumps, motors, compressors, paper machines, rolling mills, machine tools and gearboxes because all rotating machines produce vibrations that are a function of machine dynamics such as the alignment and balance of the rotating parts. Vibrations of a machine are often dominated by the rotational frequency and its multiples. Vibration measurement (depicted in Fig 1.3 through flow chart) is an effective, non-intrusive method to monitor machine condition during starting, shutdown and normal operation. for measuring vibrations. Measuring amplitude of the vibrations at certain frequencies can provide valuable information about accuracy of the shaft alignment and balance, condition of the bearings or gears, and effect on the machine due to resonance from the housings, piping and other structures. A major advantage is that vibration analysis can identify developing problems before they become too serious and cause unscheduled downtime. This can be achieved by conducting regular monitoring of machine vibrations either on continuous basis or at scheduled intervals. Regular vibration monitoring can detect deteriorating or defective bearings, mechanical looseness and worn or broken gears. Vibration analysis can also detect misalignment and unbalance before these conditions result in bearing or shaft deterioration. Therefore, vibration monitoring plays an important role in predictive maintenance.

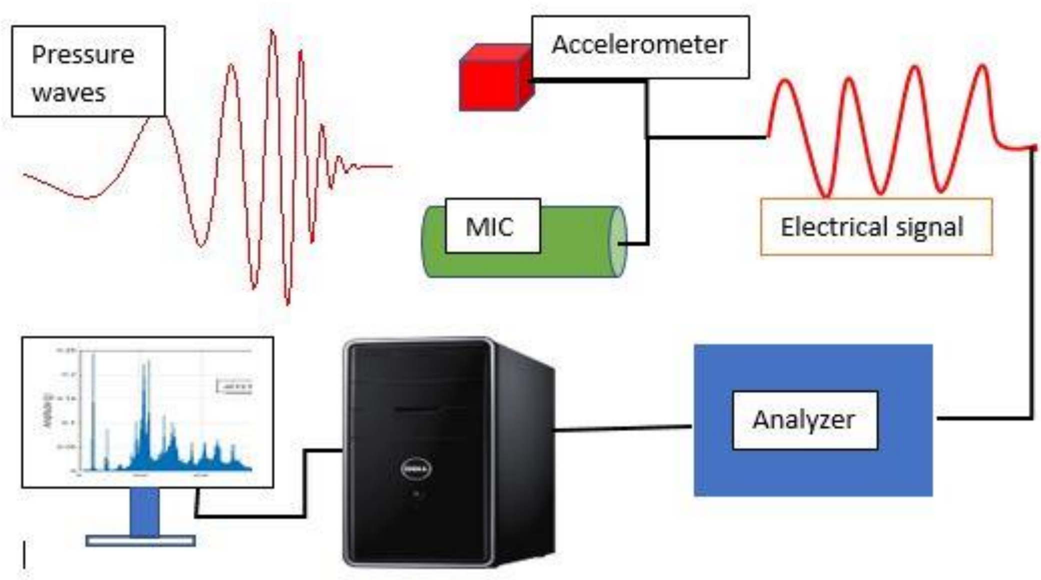


Fig.1.3: Flow chart of measurement of noise and vibrations.

1.7 Reduction of Noise and Vibrations in Gears

Since, there are many reasons responsible for generation of noise and vibrations in gear therefore it is very difficult to identify the exact cause. However, following are some important design and operation related methods or considerations for reducing noise and vibrations in a gear (***KHK STOCK GEARS***).

- **Load and speed of the gears:** Lowering rotational speed and load of the gears are helpful to decreasing noise and vibrations.
- **Type and design of the gears:** Following aspects related to type and design of gears help in reduction of noise and vibrations in a gear:

  [1] Increasing the contact length between teeth of gears reduces noise and vibrations level i.e. helical gears are quieter than the spur gears.

  [2] Use of gears having thinner teeth i.e. smaller module and larger number of teeth

  [3] Increasing rigidity of gears by increasing face width of gears and reinforcement of housing and shafts helps in reducing gear noise.

  [4] Increasing the contact ratio by decreasing the pressure angle and/or increasing the face width helps in lowering noise level of gears

[5] Eliminating interference on the tooth profile by using appropriate number of teeth, stubbing, decreasing pressure angle, chamfering the corner of the top land, and by modifying the tooth profile.

[6] Smaller backlash results in pulsating transmission and larger backlash in poor transmission efficiency. Providing proper amount of backlash in the gear pair avoids thermal jamming.

[7] Providing correct amount of crowning, end relief and profile modification help in diminishing the vibrations and noise.

- **Gear materials:** Use of materials having high damping capacity such as cast iron helps in decaying the vibrations. Plastic gears are quieter especially in light load and low speed applications.
- **Configuration of Gearbox:** Design gearbox as close to round shape and use flexible coupling between the prime mover and gears helps in reducing noise and vibrations in gearbox.
- **High quality finishing of the gears:** High quality of the gears can be ensured by minimizing errors in tooth profile, lead, pitch, runout and topography by proper combination of finishing and surface modification processes.
- **Using gears having better surface quality:** Surface quality of gears including different aspects of surface finish and surface integrity can be improved by proper finishing and/or surface properties enhancing processes. Use of conventional gear finishing processes such as grinding, lapping and honing or some advanced finishing process and running-in the gears in oil for some duration can also improve the smoothness of tooth surface which helps in reducing the noise.
- **Using proper lubrication:** Sufficient lubrication of gears ensuring hydrodynamic lubrication between the meshing gears and using high viscosity lubricant also reduces gear noise.

1.8 Finishing of Cylindrical Gears

It is evident from Fig. 1.2 that the deviations or errors in the microgeometry of gear teeth and their surface quality generally contribute more than 30% in generation of noise and vibrations in a gear. Errors induced during manufacturing of gears can be eliminated or reduced during their finishing. Many modern day applications require very high quality of gears, for example modern electric vehicles in which gearbox is the only single source of noise and vibrations in it since there is no combustion chamber. Shaving, honing, burnishing, skiving, grinding, and lapping are conventional processes for finishing cylindrical gears. But, these processes have non-overlapping capabilities and suffer from following inherent limitations (**Pathak and Jain, 2017)**:

- Their performance is dependent on mechanical properties of the workpiece gear. Except gear grinding, no process can finish hard and/or hardened gears having hardness more than 40–50 HRC.
- Sometimes these processes may introduce some errors in microgeometry and surface integrity of the gears which adversely affect their meshing mechanics. They require skilled operators and careful considerations to avoid undesired effects on the gear tooth profile.
- These processes are more costly and less productive due to early and regular breakage of cutting tools, their repair costs and initial and maintenance costs of the machines used in these processes.
- *Gear shaving* removes more material from the pitch surface of gear teeth. This deteriorates their microgeometry and flank surface topology of a gear particularly those having true involute profile.
- *Gear burnishing* is a localized cold-working process therefore it may result in some undesirable effects such as localized surface stresses and non-uniform surface characteristics. Moreover, the burnishing dies are very costly.
- *Gear grinding* may lead to two major undesirable effects: (i) small transverse grind lines on the flank surface which causes noise generation and vibration of the gears; and (ii) grinding burns which damage the surface integrity of the ground gears and can even lead to gear failure due to tooth breakage.
- *Gear lapping* adversely affects the profile of gears if performed for longer duration.

Above-mentioned limitations of the conventional processes for gear finishing do not allow a single process to simultaneously improve all the surface characteristics of a gear without inducing any adverse effect. Most of the time, more than one process is required to achieve the required surface characteristics which makes it time consuming, laborious and less productive. These limitations can be overcome by developing a non-contact, material hardness independent, more productive, more economical and sustainable gear finishing process. Consequently, some advanced or unconventional process have been explored for high quality finishing of gears such as

- Electrochemical honing (ECH) for finishing spur gears (**Naik et al., 2008**), helical gears (**Mishra et al., 2010**) and straight bevel gears (**Shaikh, 2013**).
- Pulsed-ECH (PECH) for finishing spur gears (**Mishra et al., 2012**), helical gears (**Rai, 2016**) and straight bevel gears (**Pathak, 2016)**

- Finishing of bevel gears by abrasive flow machining (AFF) by **Venkatesh et al. (2014)** and by ultrasonic assisted AFF (UA-AFF) by **Venkatesh et al. (2015)**.
- Near net-shape manufacturing of miniature spur gears by wire electric discharge machining (WEDM) process (**Gupta and Jain, 2014**).

1.9 Organization of Thesis

- **Chapter 2** presents review of the past work on gear noise and vibrations and on finishing of gears by different advanced finishing processes, the identified research gaps, the research objectives defined to bridge the identified research gaps and research methodology used in the present work.
- **Chapter 3** describes design and development of the test rig for study of noise and vibrations of spur gears along with details of the subsystems of the developed test rig.
- **Chapter 4** reports on planning and details of the experimentations for finishing of spur gears by PECH and abrasive flow finishing (AFF) processes and near net-shape manufacturing of spur gears by WEDM.
- **Chapter 5** presents results noise and vibrations of spur gears finished by different processes along with their analyses.
- **Chapter 6** highlights the conclusions of the present work and scope for future work based on the limitations of the present work.

Chapter 2

Review of Past Work

This chapter describes review of the past work on gear noise and vibrations and on finishing of gears by different advanced finishing processes, the identified research gaps, the research objectives defined to bridge the identified research gaps and research methodology used in the present work

2.1 Past Work on Finishing of Gears on their Noise and Vibrations

Akerblom and Parssinen (2002) studied effect of surface finish and geometry of tooth flanks on noise and vibrations in helical gears. They reported that transmission error is an important excitation mechanism for gear noise. They compared shaved gears and ground gears and they found that shaved gears do not seem to be nosier than ground gears even their tooth deviation are larger. Some of their important conclusions are:

- Shaved gears do not seem to be nosier than ground gears even if their tooth deviations are larger. Gears ground with threaded wheel grinding may be a little less noisy than profile ground gears.
- Poor surface finish may increase level of noise and vibrations within the range of 1 to 2 dB particularly at lower torque.
- Increased lead crowning increases level of noise and vibrations.
- Helix angle error increases noise level.
- Lower values of pitch errors may decrease the gear mesh harmonics which may decrease the overall level noise and vibrations by about 2 to 3 dB.

Liu et al. (1990) conducted 242experiments on spur gears used in headstocks of the machine tools in which they compared noise of the spur gears ground on different gear grinders. They reported that gears with better surface finish had lower noise. They reported 85 dB and 75.7 dB as maximum and minimum values of noise level respectively. They also observed that gears having smaller value of pith error, profile error and transmission error reduced the average noise level by 4 dB**.**

Jolivet et al. (2015) studied influence of finishing of tooth flank surfaces of spur gears on their noise and vibrations comparing performance of two finishing process namely grinding and power honing. They reported that ground gears produce lesser vibrations than the power honed gears and difference being 0.2 dB at first harmonic and 0.3 dB at second and third harmonic.

2.2 Past Work on Finishing of Gears by ECH and PECH

Naik et al. (2008) used ECH for finishing of spur gear made of mild steel and EN8 by ECH using different combination of $NaNO_3$ and NaCl as electrolyte and EN24 as the honing gear material. They reported an improvement up to 80% and 67% in average surface roughness (R_a) and maximum surface roughness (R_{tm}) value respectively.

Mishra et al. (2012) used PECH for finishing of spur gear made of EN8 material to investigate the effects of five parameters of PECH process on surface roughness parameters. They identified optimum values of pulse-on time as 2 ms, pulse-off time as 7 ms, finishing time of 24 minutes, gravimetric mixture of NaCl and $NaNO_3$ in a ratio of 3:1 as electrolyte composition and electrolyte temperature as 30^0 C which gave maximum improvement in the considered parameters of surface roughness.

Shaikh (2013) was probably the first researcher to explore ECH for high finishing of straight bevel gear by envisaging a novel concept of twin complementary cathode gears described by **Shaikh and Jain (2016). Shaikh (2013)** investigated effects of seven variables on percentage improvement in parameters of process productivity, microgeometry, surface roughness of straight bevel gear made of 20MnCr5 alloy steel. Following are main conclusions from his work:

- Electrolyte composition of 75% $NaNO_3$ + 25% NaCl and finishing time of 2 min was identified as optimum combination which yielded the best combination of improvements in the surface finish and the geometric accuracy. (**Shaikh and Jain, 2015)**.
- Average and maximum values of surface roughness improved by 62.7% and 32.7% respectively and quality of straight bevel gears improved from DIN 8 to DIN 7 for adjacent pitch error and DIN 7 to DIN 6 for the runout (**Shaikh et al., 2013)**.

Pathak (2016) used PECH for better quality finishing of straight bevel gears than ECH after **Pathak et al. (2015)** proved superiority of PECH over ECH for straight bevel gear finishing. Some of their achievements are as follows:

- **Pathak et al. (2014)** identified for 2 ms as pulse-on time, 4.5 ms as pulse-off time(i.e. duty cycle of 30.77%), and finishing time as 6 min as optimum values trough pilot experiments.
- Identified optimum values of electrolyte composition as 75% NaCl + 25% $NaNO_3$ applied voltage as 8 V and finishing time of 6 min results reduction in average surface roughness from 2.84 to 1.02, maximum surface roughness from 13.51 to 5.92 and improves overall gear quality from DIN 9 to DIN 6 (**Pathak et al. 2017)**.

- PECH consumes 25% less energy than ECH process does to achieve the same level of finishing (**Pathak et al. 2016)**.

2.3 Past work on Finishing of Gears by AFF

Venkatesh et al. (2014) reported the effects of extrusion pressure, abrasive mesh size, processing time and media flow rate on finishing of straight bevel gears made of EN-8 steel by AFM process. The initial surface roughness of the as received bevel gears was 1.4 to 1.8 µm. Their results indicated that the improvement in surface finish was more than 50%, however, the enhancement in material removal was marginal. It was observed that the extrusion pressure has the highest contribution of about 73 % on the process output; the other significant parameters being abrasive mesh size and processing time. Same authors **(2015)** used ultrasonic-assisted AFM (US-AFM) providing ultrasonic vibrations to the workpiece gear to enhance surface finish and to reduce finishing time of the straight bevel gears.

2.4 Past Work on Near Net-shape Manufacturing of Gears by WEDM

Gupta and Jain (2014) reported on analysis and optimization of Microgeometry parameters (i.e. total profile deviation 'F_a' and accumulated pitch deviation 'F_p') of the wire electric discharge machined fine-pitch miniature spur gears made of brass. Effects of four WEDM process parameters namely voltage, pulse-on time, pulse-off time and wire feed rate on the microgeometry of the miniature gears were analysed. Larger deviations in profile and pitch were observed with higher values of the voltage and pulse-on time, and with lower values of wire feed rate and pulse-off time. The optimized values of WEDM process parameters for manufacturing the miniature gears to get minimum deviation in profile and pitch were 9V for voltage, 0.6 µs for pulse-on time, 160 µs for pulse-off time and 13 m/min for wire feed rate. The miniature spur gear manufactured using these optimum WEDM process parameters had DIN quality number as 7 and 5 for profile and pitch respectively.

2.5 Identified Research Gap

Based on the review of the past work done following research gaps were identified on noise and vibrations of spur gears.

- No work has been reported on effect of advanced finishing processes on noise and vibrations of spur gears.
- No work has been reported on the relationship of noise and vibrations with microgeometry and surface roughness of the spur gears.

- Limited research has been reported on the microgeometry and surface integrity of spur gears.
- No work has been reported to minimize the manufacturing errors of the spur gear by AFF process.

2.6 Objectives of the Present Research Work

- Analysis and Comparison of noise and vibration levels of unfinished spur gears with
  - Same spur gears finished by ECH process. This will require fabrication of the finishing chamber for spur gear finishing by the ECH and PECH processes.
  - Same spur gears finished by the AFF process
  - Near-net shape spur gears manufactured by WEDM process
- Design and development of test rig for measurement of noise and vibration level of spur gears
- Find relationship between noise and vibrations and microgeometry and surface quality of the spur gears.
- Identifying the most critical parameters of microgeometry and surface quality which significantly affects noise and vibrations of spur gears.

2.7 Research Methodology

Following research methodology was adopted in the present work to meet the identified research objectives.

- Identification of the research objectives
- Development of test rig to measure noise and vibrations of spur gears
- Design and planning of experimental investigations
- Manufacturing of spur gears by hobbing
- Measurement of microgeometry and surface roughness of unfinished (i.e. Hobbed) spur gears
- Finishing of spur gears by AFF and PECH processes
- Near net-shaped manufacturing of spur gears by WEDM process
- Measurement of microgeometry of the finished and WEDMed spur gears
- Analysis and comparison of levels of noise and vibrations of the unfinished, finished and WEDMed spur gears

Chapter 3

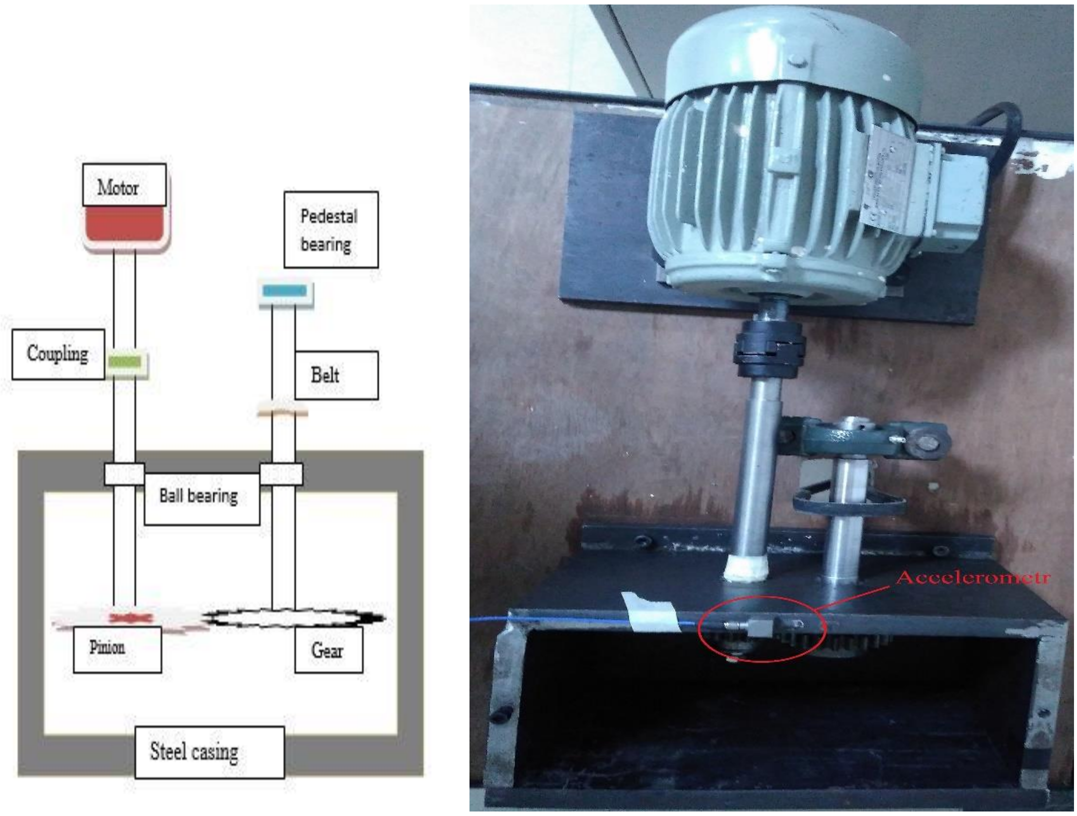
Design and Development of the Test Rig

A test rig was designed and developed to measure the noise and vibrations of the spur gears. This chapter describes details of different subsystems of the developed test rig.

3.1 Apparatus for Measurement of Noise and Vibrations

Figure 3.1a depicts the schematic diagram of top view of the developed test rig whereas Fig. 3.1b shows its photograph. Figure 3.2 illustrates the arrangement of different devices used in measurement of noise and vibrations of the spur gears. It consists of following two subsystems:

- **Test rig:** The developed test rig consists of (i) Single stage gear box to support the pinion and gear mounted on two parallel shafts in cantilever manner. Both pinion and gear are either unfinished, finished or near net-shape manufactured spur gears; (ii) an electric motor to provide rotary motion to pinion which in turn rotates the gear to which load is applied through the belt pulley arrangement as shown in Fig. 3.1b; (iii) Variable frequency drive (VFD) to vary speed of the electric motor; (iv) flexible coupling to connect the shafts of the electric motor and pinion; (v) pedestal bearing to provide end support to shaft of the gear and to prevent its deflection; (vi) casing to house the gear box; and (vii) Table to fix and support the test rig.
- **Noise and Vibration Analyzer:** It consists of (i) Accelerometer to capture signals for vibrations; (ii) Condenser type microphone to capture sound signals; (iii) Analyzer to collect the signals from the accelerometer, microphone, sound intensity probe; proximity probe, etc. and transfer them to the software for signal analysis of noise and vibrations.



(a) **(b)**

Fig. 3.1: Top view of the developed test rig: (a) schematic diagram; and (b) photograph.

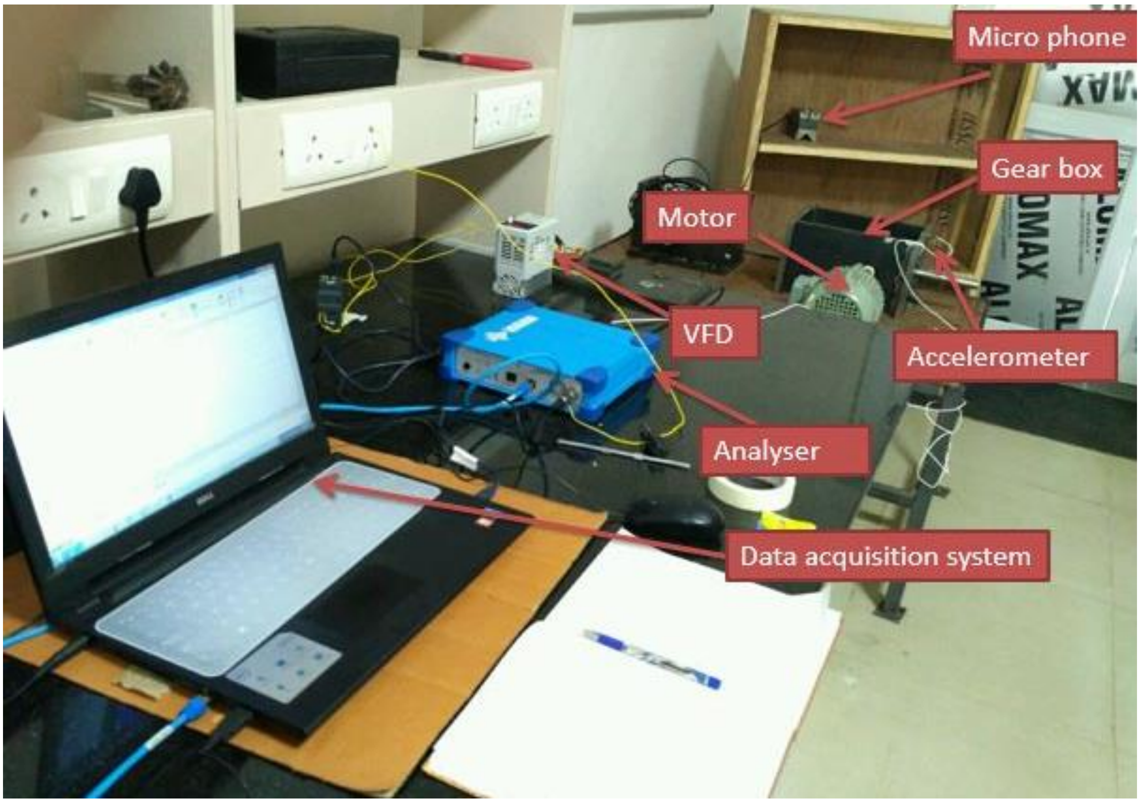


Fig. 3.2: Arrangement of the devices used to measure the noise and vibrations of spur gears.

3.2 Design and Development of Test Rig

3.2.1 Design and Fabrication of the Gear Box

Single stage gear box having parallel shaft configuration with 60 mm center distance between the input (i.e. pinion) and output (i.e. gear) shafts was designed. Dimensions of the gear box casing are 250 mm × 150 mm × 200 mm. The medium carbon steel plates of thickness 16 mm were used for making the casing for the gear box because medium carbon steel has very low damping property. Two ball bearings were put inside the plate near the electric motor for passage of input and output shafts through them and to minimize friction between the shafts and the steel plate. Two side plates, plate near the motor and the base plate were joined together by electric arc welding whereas front plate was joined to this assembly by bolts so as to provide access to the pinion and gear.

3.2.2 Selection of Bearings

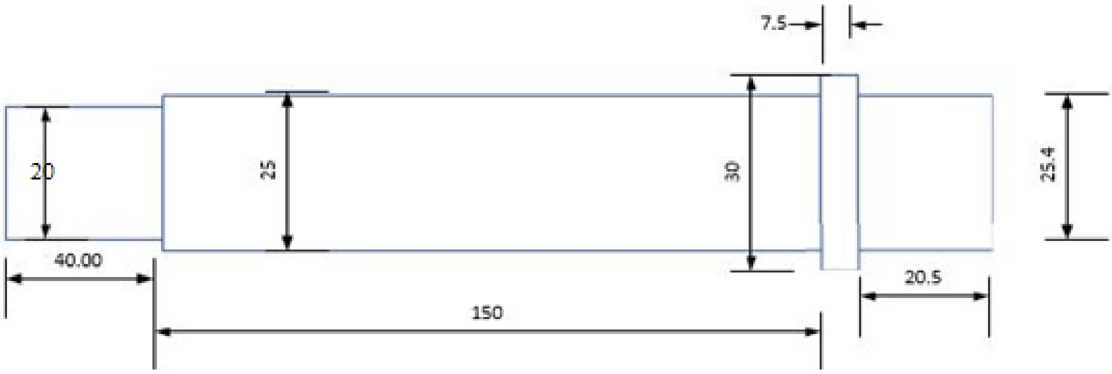
Deep grove ball bearings of 6205 designation and depicted in Fig. 3.3a were used to support the input and output shafts because these ball bearings produce very less noise and vibrations at higher speeds. They can take both radial and axial loads. The pedestal bearing used for providing end support to output shaft, which is subjected to constant radial load, and to avoid its deflection was pillow block type (depicted in Fig. 3.3b).

(a) **(b)**

Fig. 3.3: (a) deep grove ball bearing, (b) Pillow block bearing.

3.2.3 Design of the Shafts

High speed steel (having shear strength of 80 MPa) was selected as material making for input and output shafts and their diameters were calculated using maximum torque 100 Nm using the standard torsion equation and neglecting their weight. This gave 18.15 mm as their diameter. Figures 3.4a and 3.4b show the drawing and photograph of the input and output shafts used in the test rig.



(a)

(b)

Fig 3.4: Details of input and output shafts used in the test rig: (a) drawing; (b) photograph.

3.2.4 Test Rig Table

All the components of the test rig were mounted on a table having dimensions of 600 mm wide; 900 mm long; and 900 mm height (depicted in Fig. 3.5). Its frame was made of 18 mm thick L-shape angle and plywood was on its top to provide support to the test rig.

Fig. 3.5: Photograph of the supporting table for mounting the test rig.

3.3 Apparatus for Measuring Noise and Vibrations

3.3.1 Noise and Vibration Analyzer

Four channel noise and vibration analyzer (OROS OR 35) depicted in Fig. 3.6 as used for collecting the signal of noise and vibrations of the gear pair. Its associated software (*NV Gate 9.0, 3-series*) was used for analysis of the acquired signals.

Fig 3.6: Photograph of noise and vibrations analyzer.

3.3.2 Accelerometer

Accelerometer is a sensor which is used to detect and monitor vibrations in rotating machinery by acquiring acceleration. Accelerometer (shown in Fig. 3.7) of mode 3214A2 and having sensitivity as 97.86 mV/g (from **Dytran Instruments Inc.)** was used to capture signal of vibrations of the spur gears.

Fig 3.7: Photograph of accelerometer.

3.3.3 Microphone

Microphone is a transducer which converts acoustical energy (sound waves) into electrical energy (audio signal). Condenser type microphone from **Microtech Gefell** (depicted in Fig. 3.8) and having sensitivity of 42.9 mv/Pa was used in the present work.

Fig 3.8: Photograph of microphone

3.3.4 Prime Mover

A three-phase induction motor of 1 HP power capacity (shown in Fig. 3.9a) was used to rotate the input shaft of the gear box. Variable frequency drive from **L & T** (model no. **CX2000)** as shown in Fig. 3.9b was used to control the speed of the induction motor.

(a) **(b)**

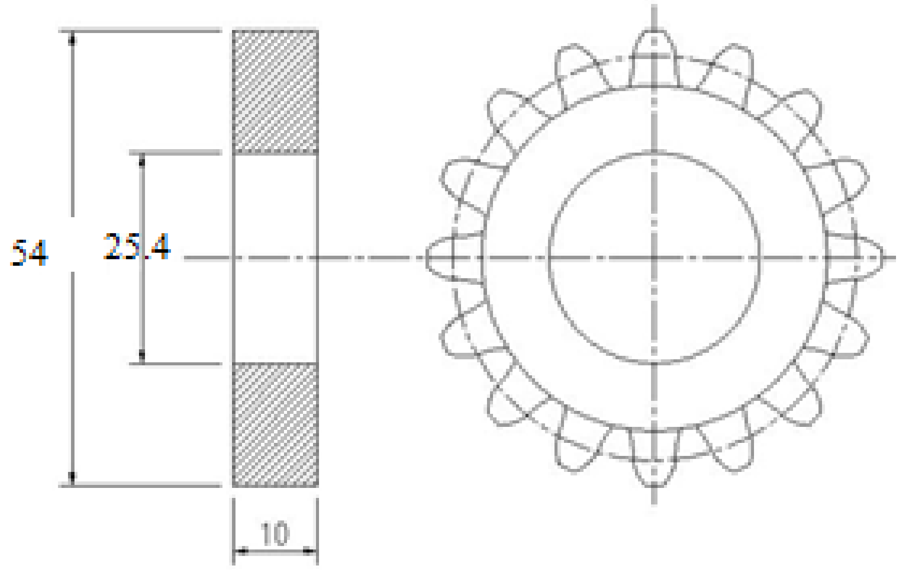
Fig 3.9: (a) Motor; (b) Variable Frequency Drive

3.4 Details of Pinion and Workpiece Gears

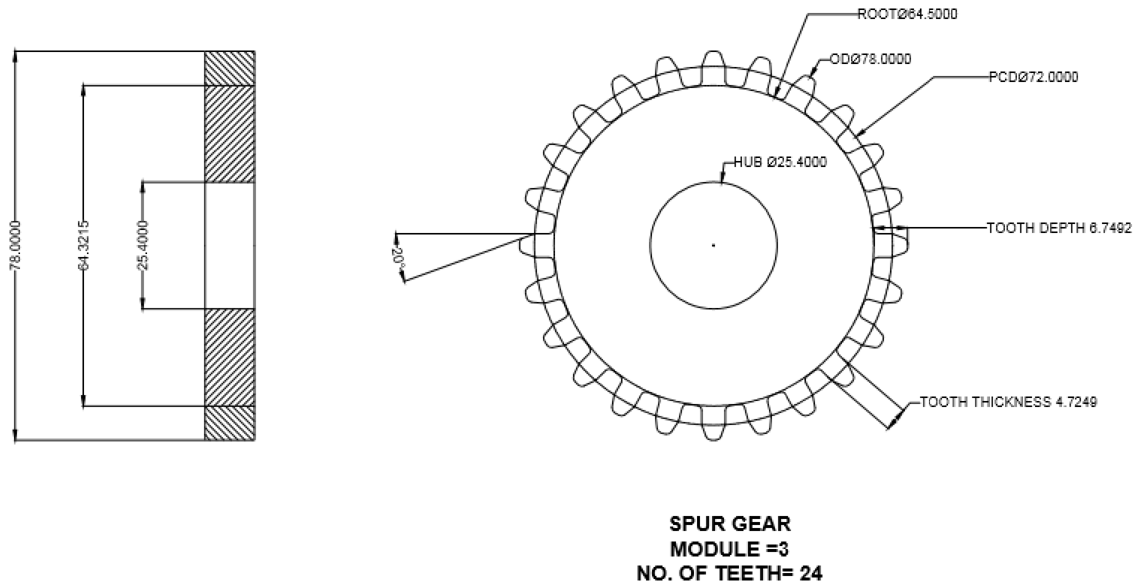
The pinion and workpiece gears used in the analysis were spur gears having 3 mm module. Workpiece gear has 24 teeth while pinion has 16 teeth. The workpiece gears and pinion were made of 20MnCr5 alloy steel. This grade of alloy steel was selected as gear material because it is the most commonly used material for the production of commercial gears for typical industrial application. Figures 3.10a and 3.10b depict the detailed drawing of pinion and workpiece gear. Table 3.1 presents their specifications.

Table 3.1: Specifications of the pinion and gear.

Parameters	Pinion	Gears	Unit
Material	20MnCr5 alloy steel		
Module	3	3	mm
Number of teeth	16	24	-
Pressure angle	20	20	degree
Pitch circle diameter	48	72	mm
Working depth	6.75	6.75	mm
Addendum circle	54	78	mm
Root circle diameter	40.5	64.5	mm



(a)



(b)

Fig. 3.10: Drawing of (a) pinion; (b) workpiece gear.

Chapter 4

Details of Experimentation

4.1 Evaluation of Microgeometry of Spur Gears

Microgeometry of the unfinished and spur gears finished by different processes and near net-shape manufactured by WEDM process was inspected in terms of their form errors [i.e. total profile error (F_a), total lead error (F_b)] and location errors [i.e. cumulative pitch error (F_p), and total runout error (F_r)]. Deutsche Normen (DIN) and American Gear Manufacturers Association (AGMA) are the universally accepted standards for denoting quality of the gears in terms of microgeometry parameters. Lower DIN number or higher AGMA number indicates better quality of the gears and vice-versa. Considered parameters of microgeometry were measured on right hand and left-hand flanks of tooth of the unfinished and finished spur gears on the computer numeral controlled (CNC) gear metrology machine **Smart-Gear** from **Wenzel Gear-Tec, Germany**. These values were used to compute average values of errors. Eq. (4.1) was used to compute average value of percentage improvement in total profile error (PIF_a).

$$Avg.PIF_a = \frac{Avg. F_a\ value\ of\ unfinished\ gear - Avg.\ F_a\ value\ of\ finished\ gear}{Avg.\ F_a\ value\ of\ unfinished\ gear} 100 \qquad (4.1)$$

Similarly, average values of percentage improvements were computed for error in total lead error (F_b) and cumulative pitch (PIF_p). Concept of runout evaluation yields single value therefore percentage improvement in runout (PIF_r) was computed using Eq. 4.2.

$$PIF_r = \frac{F_r\ value\ of\ unfinished\ gear - F_r\ value\ of\ finished\ gear}{F_r\ value\ of\ unfinished\ gear} 100 \qquad (4.2)$$

4.2 Finishing of Spur Gears by AFF Process

In recent year development in material and manufacturing technology grew up very rapidly to achieve better quality at minimum cost. Major focuses of this new development are on reducing the cycle time and improve the quality, performance and life of gears. Abrasive flow finishing (AFF) is an advanced finishing process which was conceived in 1960s with initial applications for deburring of the components manufactured by electric discharge machining (EDM) process. Subsequently, its range of material and shape applications is continuously growing.

4.2.1 Working Principle of AFF Process

AFF process uses a medium in the form of viscoelastic self-deformable putty filled in the two oppositely placed cylinders between which the fixture holding the workpiece is sandwiched. The AFF medium is forced pass back and forth through the workpiece thus imparting it very high-quality finish, sometimes even mirror-like finish, by shearing off the peaks from the surfaces of the workpiece.

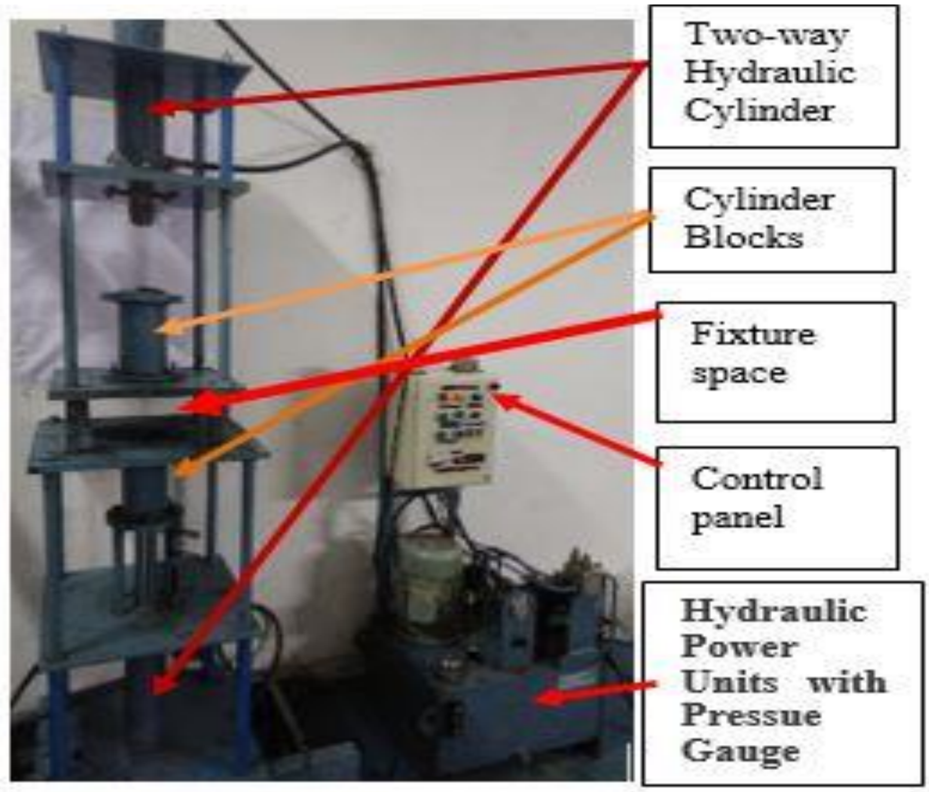


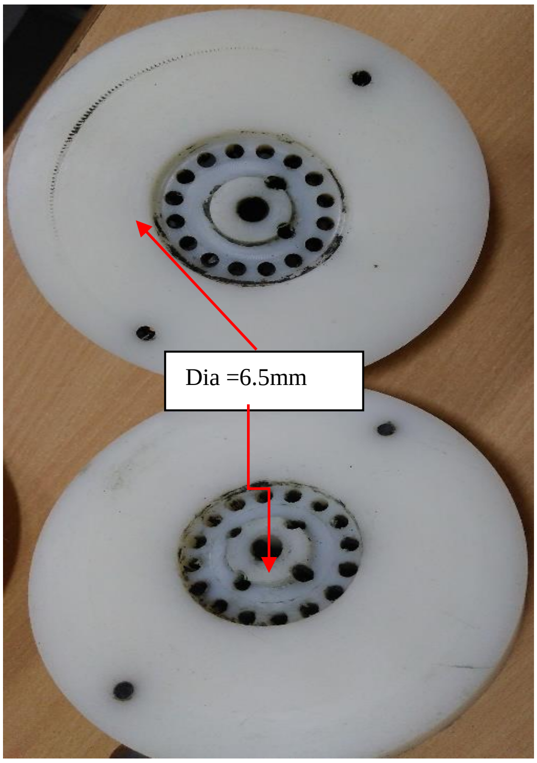
Fig 4.1: Photograph of AFF apparatus developed for gear finishing by Anand C Petare.

4.2.2 Design of Fixtures for AFF of the Spur Gears

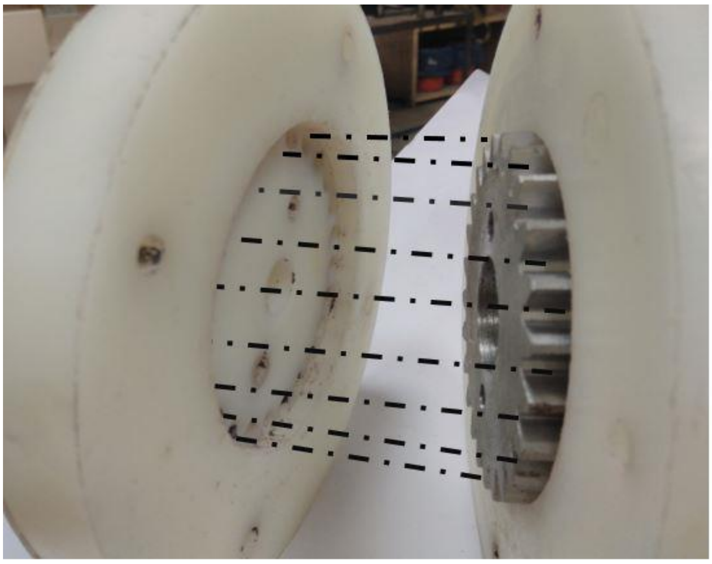
Workpiece gear holding fixture is the most important component of the AFF apparatus because it ensures holding and exact locating of the workpiece gear in the desired position during its finishing by AFF process. Two sets of fixture were designed and developed for holding the pinion and workpiece as depicted in Figs. 4.2a and 4.2b respectively. Each fixture has two cylindrical plates having circumferential holes as shown in Fig. 4.2 for facilitating back and forth movement of AFF medium over flank surfaces of two consecutive teeth of the spur gear schematically depicted in Fig. 4.2c. Metalon was used to make these fixture sets due to its non-reactive nature with AFF medium and ease of machining it.

4.2.3 Components of AFF Machine

The AFF machine has two hydraulic cylinders, two medium-containing cylinders, workpiece fixture, limit switches, supporting structure, pressure control valve, stroke counter, and hydraulic power unit. AFF medium is moved back and forth from one medium-containing cylinder to other medium-containing cylinder by the pistons of hydraulic cylinders operated by hydraulic power unit. Workpiece is fixed in the fixture clamped between the medium-containing cylinders.



(a) (b)



(c)

Fig 4.2: Gear holding fixture developed (a) pinion; (b) gear; and (c) fixture assembly showing movement of the AFF medium.

4.2.4 AFF Medium

The AFF medium is in the form of semi-solid putty having self-deforming ability which is forced through a passageway or restrictions either in one direction or in both directions. A mixture of silly putty, silicon carbide abrasive grains and silicon oil as lubricant was used as AFF medium in the present work. It was resilient enough to act as a self-deforming grinding stone when forced through the workpiece.

4.2.5 Parameters Used in Spur Gears Finishing by AFF

Three pinions and three workpiece gears (i.e. six experiments) were finished using the optimum values of AFF parameters identified by **Petare and Jain (2017).** These values are: 50 bar as extrusion pressure; 150 mesh as size of abrasives; 30 (wt. %) as gravimetric concentration of abrasives in the AFF medium; and 15 minutes as finishing time.

4.2.6 Procedure of Finishing Spur Gears by AFF

All the spur gears were finishing by AFF process using the following procedure:

- All the considered responses were measured for all the unfinished (i.e. hobbed) pinion and gears.
- AFF Medium of the required composition and concentration was prepared by manual mixing and keeping in view all the required considerations.
- Filling the AFF medium in the medium-containing cylinders
- Mounting and fixing of the workpiece gear or pinion in the corresponding fixture and ensuring that there is no rotation of gear or pinion in the fixture and axis of the gear or pinion is parallel to the axis of central hole provided in the corresponding fixture.
- Clamped both the plates of the fixture to the AFF apparatus with bolts and ensuring that there is no leakage of the AFF medium during the gear finishing.
- Reciprocation speed of the AFF medium was maintained by pressure exerted by hydraulic cylinders and stroke length was set by limit switch.
- Extrusion pressure was maintained by hydraulic pump.
- Finishing time was measured using a stop watch and the experiment was stopped immediately after completion of the finishing time.
- After each experiment, the workpiece gear was properly washed with tap water and cleaned with cotton and dipped in the lubricating oil so as to avoid its rusting due to exposure to putty in the finishing fixture.
- All the considered responses were measured for the all the gears finished by AFF.

4.2.7 Results of Spur Gear Finishing by AFF

Table 4.1 presents microgeometry parameters for the three pinions and three gears finished by AFF process. It can be observed from this table that AFF improves microgeometry of the spur gears with the best values of average percentage improvement in total profile error (PIF_a), total lead error (PIF_b), cumulative pitch error (PIF_p) and in total runout error (PIF_r) being as 17.5% (for gear-2); 41% (for pionion-3); 13.0% (for gear-2); and 3.8% (for gear-1) respectively. It can also be noted that at the same input parameters the improvement in the microgeometry is different for all the finished gears and pinions. Maximum value of percentage improvement in a parameter of microgeometry implies minimum value of that parameter after finishing the gear.

4.3 Finishing of Spur Gears by PECH process

ECH is a hybrid finishing process which combine the capabilities and advantages of electrochemical finishing (ECF) with mechanical honing and simultaneously overcome their individual limitations. When pulsed DC power is used instead of continuous DC power then the process is referred as pulsed-ECH (PECH). Main capabilities of ECF process include: performance independent of mechanical property imparting capability to finish material of any hardness, production of stress-free and crack-free surface, higher material removal rate (MRR) and negligible tool wear. Main capabilities of honing are: ability to correct the errors in microgeometry and controlled generation of the functional surfaces. Main limitation of ECM process is passivation of anodic workpiece surface due to metal oxides formation caused by evolution of oxygen gas at anode during its electrolytic dissolution. This anode passivation prohibits further electrolytic dissolution of the workpiece. Major limitations of honing process include limited life of honing tool, low productivity, incapability of finishing a hardened workpiece and possibility of mechanical damage such as micro-cracks, hardness alternation and plastic deformation to the workpiece material. This makes ECH as an ideal choice to explore as an alternative, superior and economical finishing process for different types of gears.

4.3.1 Process Principle of PECH

Chen et al. (1981) proposed concept of finishing spur gears by ECH process as depicted in Fig. 4.3. In this, the workpiece gear '1' is clamped between centers of the work table, which is reciprocating axially as indicated by the arrowhead '3'. The cathode in the ECM process should be electrically conductive to produce electrolysis action, but in finishing of gears by ECH, the cathode gear is in constant mesh with workpiece gear, which will cause a short circuit during the process. Therefore, to avoid it, the cathode gear consists of a gear '7' made of a conducting material sandwiched between two insulating gears '6'. The conducting gear is undercut by an amount *'δ'* as compared to the non-conducting gears thus resulting in an inter-electrode gap (IEG) of δ. The cathode has the same involute profile as the workpiece. The axis of the shaft on which the cathode is mounted is parallel to the axis of workpiece gear. A full stream of electrolyte is supplied to the IEG *'δ'* and a DC current is passed through it. During the process of material removal, the electrolyte forms a non-conducting metal oxide protective film on the flank surfaces of the workpiece gear which prohibits their further finishing by electrolytic dissolution. This layer is scraped by the honing gear when it comes in contact with a cross axis arranged honing gear '2'.

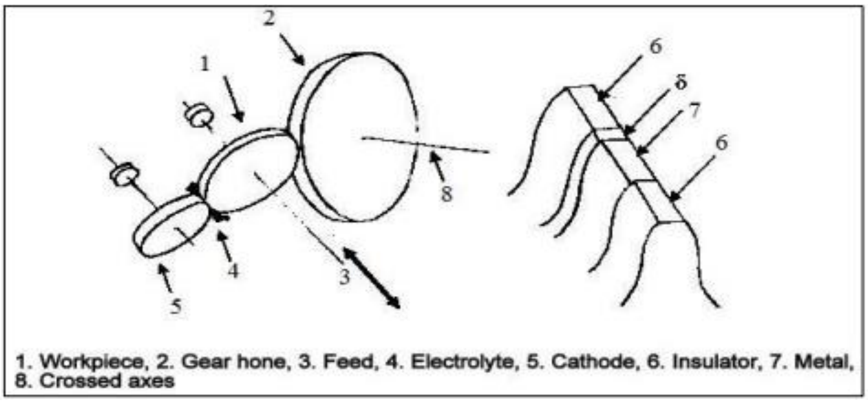


Fig. 4.3: Concept of finishing spur gears by ECH process proposed by **Chen et al. (1981)**.

The existing finishing chamber developed by **Pathak (2016)** for finishing the straight bevel gears and subsequently modified by Rai (2016) for finishing the single helical gears was made suitable for finishing the spur gears by PECH in the present by (i) Designing and fabricating the required cathode gear for spur gear finishing; (ii) using spur gear made of heat treated 20MnCr5 alloy steel as honing gear instead of helical gear as proposed by **Chen et al. (1981)**. This implies that the honing gear was not aligned in the cross-axis manner with respect to the workpiece gear. Figure 4.4 depicts the photograph of the modified finishing chamber which was used for finishing of spur gears.

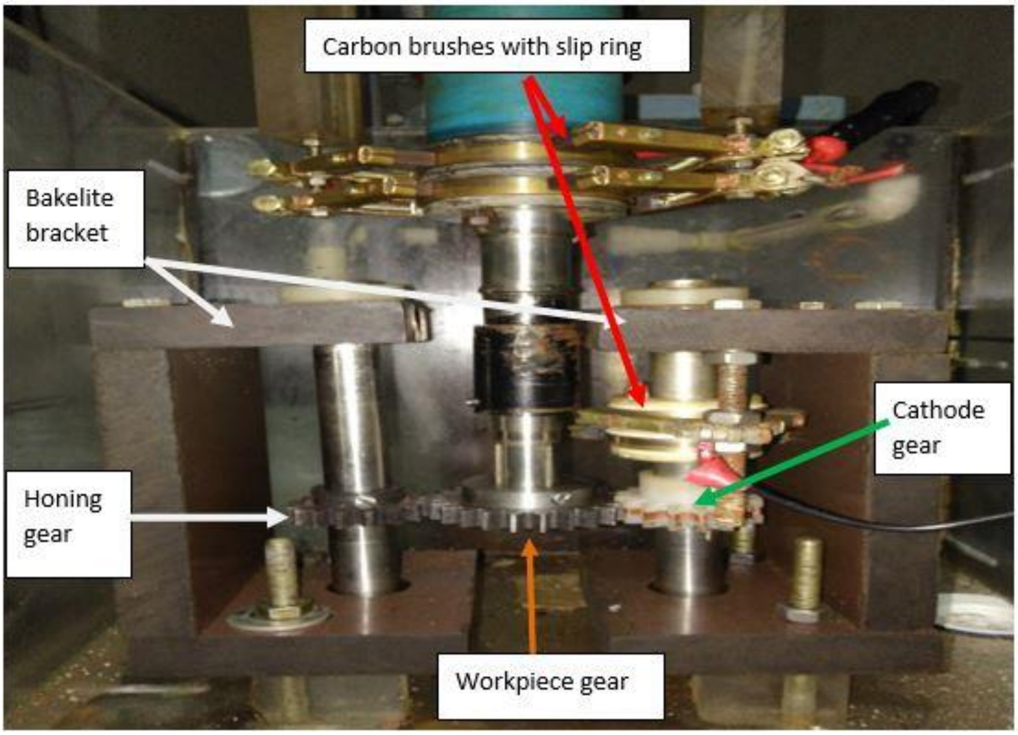


Fig.4.4: Photograph of the finishing chamber used for finishing spur gears by PECH.

4.3.2 Parameters Used in Spur Gears Finishing by PECH

Two pinion and two gears were finished by PECH process using the optimum values of PECH process parameters identified by **Rai (2016**). This included: 3 ms as pulse-on time; 6 ms as pulse-off time; 16 Volts as voltage; 20 A as current; 75 % NaCl + 25% $NaNO_3$ as electrolyte composition; 7.5% as electrolyte concentration; 30 liter per minute as electrolyte flow rate; 30^{o}C as temperature of the electrolyte; 40 rpm as rotary speed of the workpiece gear; 8 minutes as finishing time; and maintaining IEG of 2 mm.

4.2.3 Procedure of Finishing Spur Gears by PECH

Following procedure was used for finishing the pinion and gears by PECH process:

- All considered responses were measured for all the unfinished gears.
- Electrolyte of the required composition and concentration was prepared in the electrolyte storing tank. Electrolyte temperature and electrolyte flow rate were set at the required value using the temperature control unit and flow control system.
- Before providing rotary speed to the workpiece gear, proper meshing between the workpiece, honing and cathode gear was ensured so that it does not produce noise and vibration due to misalignment between their shafts.
- Rotary speed was maintained at the required value using the motion controller arrangement attached with the DC motor.
- Values of applied voltage, pulse-on time and pulse-off time and current were set as per the requirements and were controlled by computer controlled DC pulsed power supply.
- Finishing time was measured using a stop watch and the experiment was stopped immediately after completion of the desired finishing time.
- After each experiment, the workpiece gear was properly washed with tap water and cleaned with cotton and dipped in the lubricating oil so as to avoid its rusting due to exposure to corrosive electrolyte in the finishing chamber.
- All the considered responses were measured for the all the gears finished by PECH.

4.3.4 Results of Spur Gear Finishing by PECH

Table 4.1 presents microgeometry parameters for the tw pinion and two gears finished by PECH process. It can be observed from this table that in some cases finishing by PECH has deteriorated microgeometry of the spur gears which is indicated by negative values of percentage improvements in microgeometry parameters. But, in most of the cases it has improved microgeometry of the spur gears with the best values of average percentage improvement in total profile error (PIF_a), total lead error (PIF_b), cumulative pitch error (PIF_p) and in total runout error (PIF_r) being as 18.8% (for gear-1); 33.3% (for pionion-2); 33.2% (for gear-1); and 20.2% (for pinion-1) respectively.

Table 4.1: Microgeometry parameters for the pinion and gears finished by AFF and PECH process.

Run no.	**Parameters of microgeometry for the pinion and gears finished by AFF process**											
	Total Profile Error 'F_a'			Total Lead Error 'F_b'			Cumulative Pitch Error 'F_p'			Runout Error 'F_r'		
	Avg. F_a before finishing (μm)	Avg. F_a after finishing (μm)	**Avg. PIF_a (%)**	Avg. F_b before finishing (μm)	Avg. F_b after finishing (μm)	**Avg. PIF_b (%)**	Avg. F_p before finishing (μm)	Avg. F_p after finishing (μm)	**Avg. PIF_p (%)**	Total F_r before finishing (μm)	Total F_r after finishing (μm)	**Avg. PIF_b (%)**
Pinion-1	172.8	143.8	16.8	88.1	57.6	34.6	88.1	79.3	10.0	165.5	162.2	2.0
Pinion-2	160.2	136.2	15.0	67.9	45.3	33.3	67.9	60.1	11.5	150.7	146.5	2.8
Pinion-3	364.7	317.3	13.0	22.4	13.2	**41.0**	22.4	19.5	12.8	148.8	144.6	2.8
Gear-1	101.5	92.4	9.0	59.1	40.9	30.8	59.1	52.0	12.0	149.2	143.5	**3.8**
Gear-2	165.8	136.8	**17.5**	65.2	42.5	34.8	54.2	47.1	**13.0**	170.3	165.7	2.7
Gear-3	170.5	141.5	17.0	89.5	62.7	29.9	67.0	59.8	10.8	162.5	159.4	1.9
	Parameters of microgeometry for the pinion and gears finished by PECH process											
Pinion-1	243	199.2	18.0	88.1	101.6	-15.4	88.1	60.3	31.5	165.5	132.2	**20.2**
Pinion-2	160.2	134.2	16.3	67.9	45.3	**33.3**	67.9	60.1	11.5	180.7	220.5	-21.7
Gear-1	174.4	138.2	**18.8**	38.6	26.2	30.6	272.8	182.7	**33.2**	302.4	255.4	15.4
Gear-2	165.8	301.5	-45.0	60.2	42.1	30.0	301.4	331.9	-10.1	170.3	145.7	14.4

4.4 Near Net-shape Manufacturing of Spur Gears by WEDM

WEDM process is a thermo-electric erosion process in which workpiece material is removed by melting and vaporization caused due to series of electric sparks occurring between a very thin wire and electrically conductive workpiece. A high frequency DC pulse power is used in the inter electrode gap (IEG) between thin wire and workpiece which is flushed away by suitable dielectric medium (generally deionized water) having relatively lower break down voltage. This causes occurrence of tiny spark. Energy contained in tiny spark remove little amount of material from the surface of electrically conductive workpiece. Occurrence of a large number of such tiny sparks between the workpiece and wire electrode causes the erosion of the workpiece (**Gupta and Jain, 2014**).

4.4.1 Design of Experiments

Full factorial design of experiments requires large number of experiments to be carried out which becomes laborious, time consuming and complicated as number of factors (i.e. independent parameters) increases. To overcome this problem Taguchi suggested fractional factorial design of experiment approach using concept of robust design and orthogonal array to get maximum information by conducting minimum number of experiments but carefully and rationally designed. Taguchi L_9 orthogonal array was selected in the present work by varying voltage, pulse-on time, and pulse-off time at three levels and to identify their optimum values experimentally for near net-shape manufacturing of spur gears by WEDM process. Table 4.2 presents the values of the variable and fixed parameters of WEDM process used in spur gear manufacturing

Table 4.2: Values of variable and fixed parameters of WEDM used in near net-shape manufacturing of spur gears.

S. No.	Parameter name	Values used	unit
Variable parameters			
01	Voltage	12; 16; 20	volt
02	Pulse-on time	0.6; 0.8; 1.0	µs
03	Pulse-off time	39.5; 44.5; 49.5	µs
Fixed parameters			
04	Current	20	ampere
05	Wire feed rate	4	m/min
06	Wire tension	1.3	kg

4.4.2 Results of Spur Gear Manufactured by WEDM

Table 4.3 shows that the optimised input parameters for minimisation of geometry error are **V_{opt}=12 V, T_{on}=1µs , T_{off}=49.5µs**. the optimised parameters are different for profile,pitch & lead errors therefore on the basis of above analysis it would be difficult to report a unique optimised parameter.

Table 4.3: Results of near net-shape manufactured spur gear by WEDM.

Sr. No.	WEDM process parameters			Microgeometry parameters			
	Voltage (V)	Pulse-on time (µs)	Pulse-off time (µs)	Total profile error (F_a) (µm)	Total lead error (F_b) (µm)	Cumulative pitch error (F_p) (µm)	Runout error (F_r) (µm)
1	12	0.6	39.5	67.3	36	171.3	240.9
2	12	0.8	44.5	59.8	7	208.6	59
3	**12**	**1**	**49.5**	**47**	**3.8**	**60**	**83.4**
4	16	0.6	44.5	57.9	32.7	119.2	53.4
5	16	0.8	49.5	45.6	4.1	64.3	71.4
6	16	1	39.5	65.0	10.1	60.9	50.4
7	20	0.6	49.5	69.5	8.3	184.7	94
8	20	0.8	39.5	72.5	29.2	233.5	255.2
9	20	1	44.5	71.5	27	176.6	84.2

From the table 4.3, it can be noted that out of all spur gears manufactured corresponding to nine experiments, spur gear manufactured using parameters of experiment no 3 had mimum values of total lead error (3.8 µm), cumulative pitch error (60 µm), 2nd minimum value of total profile error (47 µm; gear-5 has minimum value of 45.6 µm), and 5th minimum value of total runout error (83.4 µm; is gear-6 has minimum value of 50.4 µm). Therefore, it was considered to be the best manufactured spur gear by WEDM process.

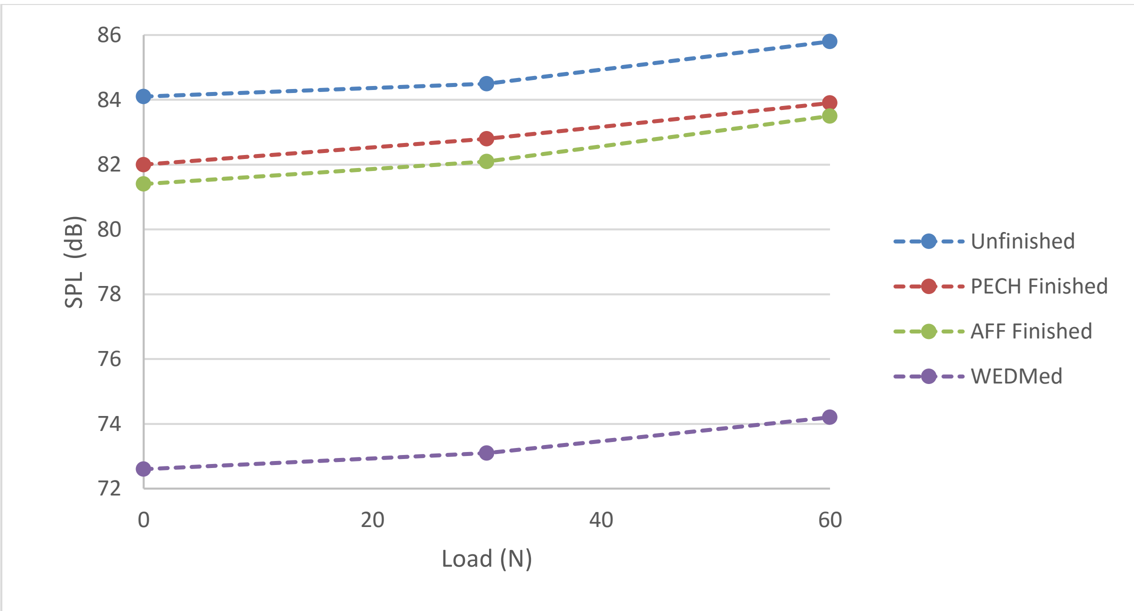
Chapter 5

Results and Discussion

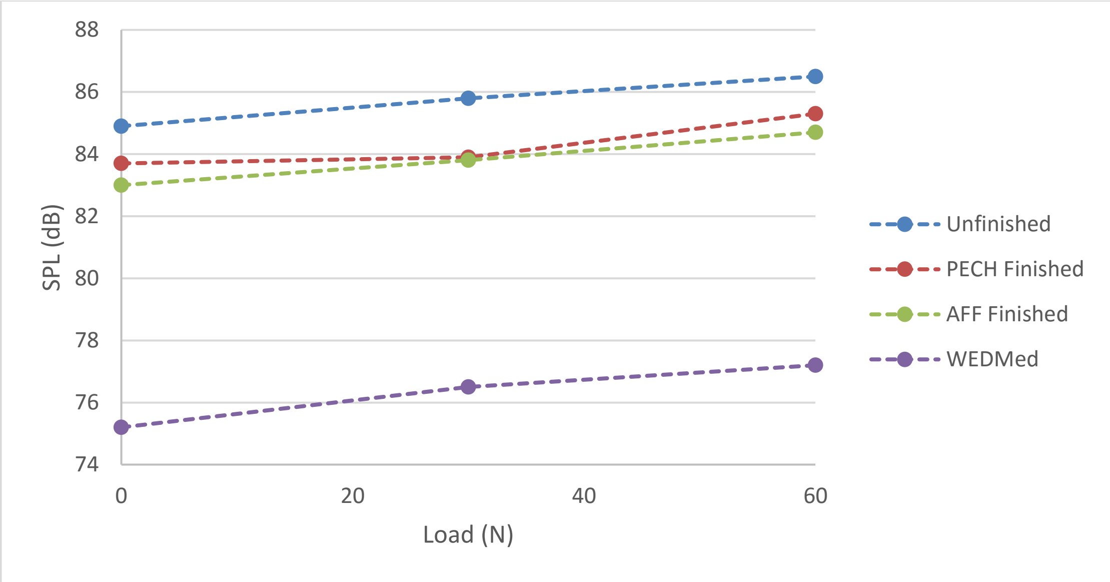
This chapter describes results of measurement of noise and vibrations obtained by meshing the pair of pinion and gear finished by AFF process, PECH process and near net-shape manufactured pair of pinion and gear by WEDM process using the developed test rig and the noise and vibration analyzer. Table 5.1 presents the results of noise and vibrations values for different spur gear pairs.

5.1 Results for Noise Measurement

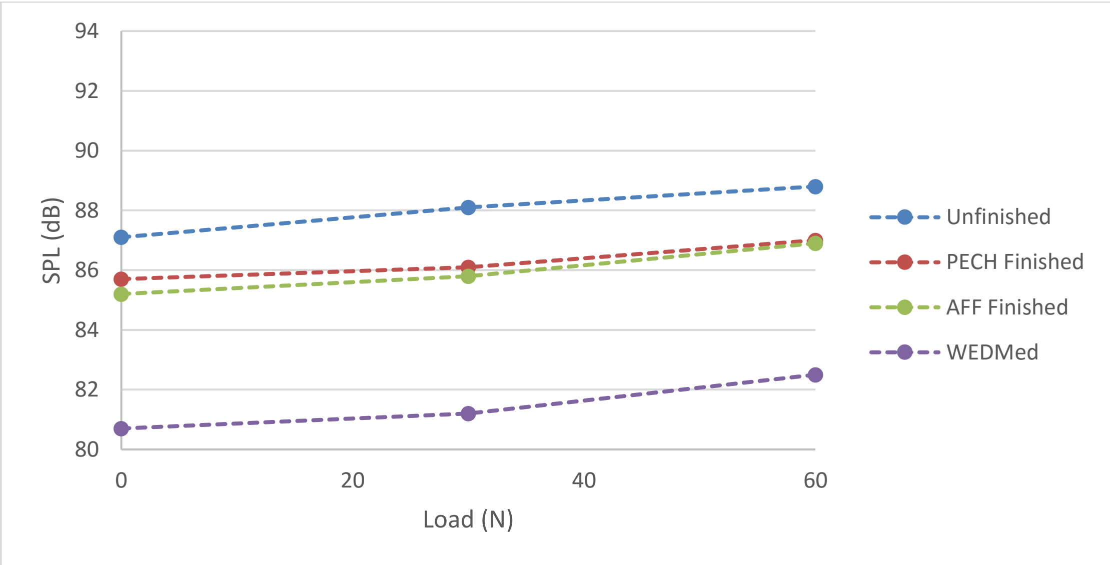
Figure 5.1 depicts the variation in sound pressure level (SPL) with applied load for unfinished spur gear and pinion pair, PECH finished spur gear and pinion pair, AFF finished spur gear and pinion pair and near net-shaped manufactured spur gear and pinion pair by WEDM process at different speed of rotation i.e. 250 rpm (Fig. 5.1a); 500 rpm (Fig. 5.1b); and 750 rpm (Fig. 5.1c). It is evident from these figures that (i) SPL increases with load at all the speeds of rotation for all the gear pairs; (ii) SPL of WEDM manufactured near-net-shape gear pair is minimum at all the speeds of rotation due to smaller values of errors in microgeometry as compared to the gear pairs finished by AFF and PECH processes. Unfinished gear pair has maximum values of SPL at all the rotational speeds; and (iii) the AFF finished gear pair is less noisy than the PECH finished gear pair at all the speeds of rotation.



(a)



(b)

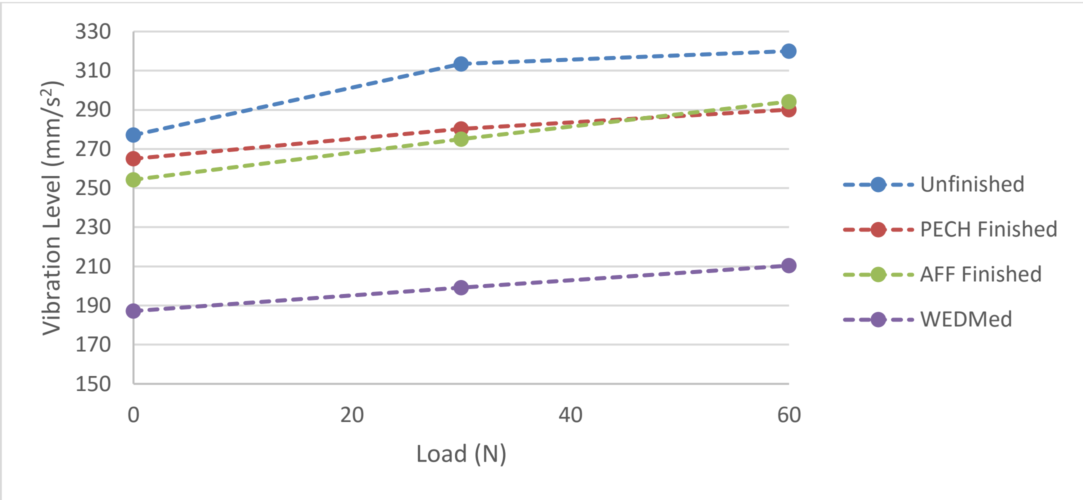


(c)

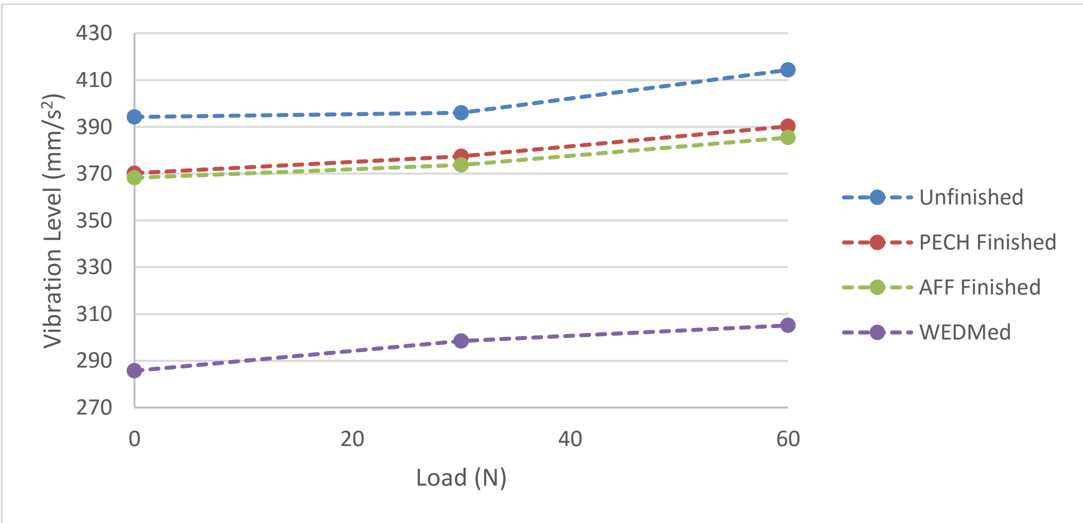
Fig 5.1: Variation of sound pressure level (SPL) with applied load for unfinished spur gear pair, PECH finished spur gear pair, AFF finished spur gear pair and near net-shaped manufactured spur gear pair by WEDM process at different speed of rotation: (a) 250 rpm; (b) 500 rpm; and (c) 750 rpm.

5.2 Results for Measurement of Vibrations

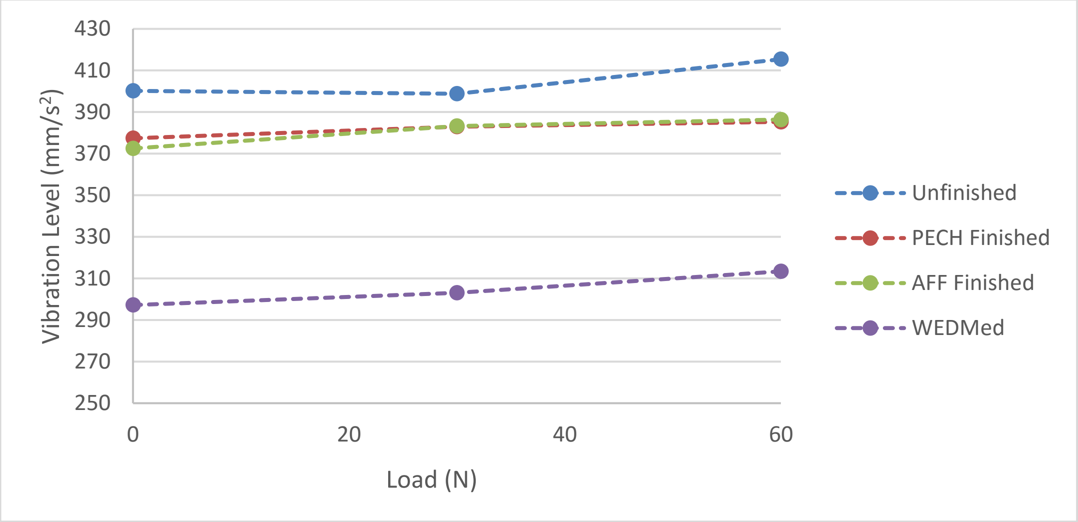
Figure 5.2 depicts the variation in vibration level with applied load for unfinished spur gear and pinion pair, PECH finished spur gear and pinion pair, AFF finished spur gear and pinion pair and WEDM manufactured near net-shaped manufactured spur gear and pinion pair at different speed of rotation i.e. 250 rpm (Fig. 5.2a); 500 rpm (Fig. 5.2b); and 750 rpm (Fig. 5.2c). It is evident from these figures that (i) Vibration level increases with load at all the speeds of rotation for all the gear pairs; (ii) Vibration level of WEDM manufactured near-net-shape gear pair is minimum at all the speeds of rotation due to smaller values of errors in microgeometry as compared to the gear pairs finished by AFF and PECH processes. Unfinished gear pair has maximum values of vibration level at all the rotational speeds; and (iii) there is not much difference in the vibration levels of AFF finished gear pair and PECH finished gear pair at all the speeds of rotation.



(a)



(b)



(c)

Fig 5.2: Variation of RMS value of vibration level with applied load for unfinished spur gear pair, PECH finished spur gear pair, AFF finished spur gear pair and near net-shaped manufactured spur gear pair by WEDM process at different speed of rotation: (a) 250 rpm; (b) 500 rpm; and (c) 750 rpm.

Table 5.1: RMS values of noise and vibrations at different rotary speed and load along with microgeometry parameters for spur gear finished by AFF and PECH processes.

Gear condition		Parameters of microgeometry				Load (N)	RMS value of noise (dB)			RMS value of vibrations (mm/s^2)		
		Average value of total profile error (F_a) (µm)	Average value of total lead error (F_b) (µm)	Average value of cumulative pitch error (F_p) (µm)	Runout error (F_r) (µm)		250 rpm	500 rpm	750 rpm	250 rpm	500 rpm	750 rpm
Unfinished	Pinion-1	243	88.1	88.7	165.5	0	84.1	84.9	87.1	277.1	394.2	400.2
	Gear-1	174.4	38.6	272.8	302.4	30	84.5	85.8	88.1	313.4	396	398.8
	Pinion-2	160.2	67.9	178.1	220.7	60	85.8	86.5	88.8	320	414.3	415.4
	Gear-2	342.8	60.2	301.4	170.3							
AFF finished	Pinion-1	136.2	45.3	60.1	146.5	0	81.4	83	85.7	254.3	368.2	372.5
	Gear-1	92.4	40.9	52	143.5	30	82.1	83.8	86.1	275	373.7	383.2
	Pinion-2	143.8	57.6	79.3	162.2	60	83.5	84.7	87	294.4	385.4	386.4
	Gear-2	136.8	42.5	47.1	165.7							
PECH finished	Pinion-1	199.2	101.6	60.3	132.2	0	82	83.7	85.2	265	370.2	377.4
	Gear-1	138.2	26.2	182.7	225.4	30	82.8	83.9	85.8	280.2	377.4	383.0
	Pinion-2	134.2	45.3	60.1	220.5	60	83.9	85.3	86.9	290.1	390.2	385.3
	Gear-2	301.5	42.1	331.9	145.7							
WEDM manufactured near net-shape	Pinion-1	47	3.8	60	83.4	0	72.6	75.2	80.7	187.2	285.7	297.2
	Gear-1	67.3	36	171.3	240.9	30	73.1	76.5	81.8	199.1	298.5	303.1
	Pinion-2	57.9	32.7	119.2	53.4	60	74.2	77.2	82.4	210.4	305.1	313.4
	Gear-2	59.8	7	208.6	59							

Chapter 6

Conclusion and Scope for the Future Work

This chapter presents the conclusions based on measured values and scope for future work.

6.1 Conclusions

Following conclusions can be summarized from the present research work-

- Increase in speed and/or load on the gear box increases the level of noise and vibrations by some notable magnitude.
- Gear pair finished by AFF process have lower errors in microgeometry as compared to PECH finished gear pair and have low level of noise and vibrations at most of conditions.
- Noise level of unfinished gear is lowered down by 1.4 dB by finishing them by PECH process and 2.1 dB by the AFF process.
- Near net-shape manufactured gear pairs by WEDM process have minimum noise and vibration level at all operating conditions.
- Gear pair manufactured by WEDM is less noisy than the unfinished gear pair by a maximum amount of 10.5 dB.
- Gear pair manufactured by WEDM process, lowers down the vibration amplitude by 100.6 mm/s^2 as compared to unfinished gear and by 75.1 mm/s^2 and 72.5 mm/s^2 as compared to PECH and AFF finished gear pair respectively.

6.2 Scope for the Future Work

Since, present work was very first attempt to study dependence of noise and vibrations of spur gears on microgeometry and compare noise and vibrations of unfinished spur gear pair with spur gear pairs finished by advanced processes, therefore it might have certain limitations. Following is scope for future work:

- Comparing noise and vibrations of spur gears finished by other unconventional or advanced finishing processes such as ultrasonic machining (USM), abrasive water jet machining (AWJM) with the unfinished spur gears.
- Comparing noise and vibrations of spur gears manufactured by other advanced manufacturing processes for spur gears such laser beam machining (LBM), electron beam machining (LBM).
- Comparing noise and vibrations of the gear pair finished by unconventional finishing processes and conventional finishing processes.

- Developing analytical or semi-empirical relationship between quality of gears and level of noise and vibrations.
- Developing relationship between microgeometry and surface roughness of spur gears with the level of noise and vibrations and identifying the most critical parameters which affect the noise and vibrations level.

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Appendix: Specifications of the Measuring Instruments

CNC Gear Metrology Machine (Centre of Excellence in Gear Engineering, IIT Indore)

Make: Wenzel GearTec, Germany	
Model: Smart 500	
External Gear Diameter Range: 5-270 mm	
Internal Diameter: >12 mm	
Range of Module: 0.4 – 15 mm	
Helix angle: <90°	
Accuracy for 3D Measurement	MPEe: 4.5+L/250 µm MPEp: 4.5 µm MPEthp: 5 µm