Design and Development of Double Flank Roll Tester for Cylindrical Gears

M.Tech. Thesis

By

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Discipline of Mechanical Engineering

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree ***of***
Master of Technology

by

Rajat Kasliwal

Discipline of Mechanical Engineering
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Candidate's Declaration

I here by certify that work which is being presented in the thesis entitled **Design and Development of Double Flank Roll Tester for Cylindrical Gears** 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 July 2015 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.

Rajat Kasliwal

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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)**

Rajat Kasliwal 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 one of the most commonly used devices for both engineering and non-engineering applications offering an elegant solution to the problem of effective power and/or motion transmission. Modern gear drive design must provide quiet and reliable performance at high power, which can only be achieved by using gears which have accurate geometry like of Involute helicoid system. Metrology or inspection of gears can be divided into two subareas functional testing and analytical testing. ***Analytical testing*** of a gear determines different parameters describing its microgeometry such parameters describing form of its teeth (i.e. profile and lead), parameters describing location of its teeth (i.e. pitch and runout), and parameters describing topology of its teeth. It does not use any master or reference gear. ***Functional testing*** of gears is qualitative test which determines whether the manufactured gear will have functional performance as intended or not i.e. it can be considered as an

inspection by attributes

When two gears are in mesh with each other, any errors in tooth form, pitch and concentricity of pitch line causes variation in their center distance. According to method of contact between the rolling gears, functional testing can either be performed as single flank roll testing or double flank roll testing. Accordingly they provide different information. *Single flank roll testing* provides information about tooth-to-tooth transmission error, *profile conjugacy* (in terms of total transmission error), cumulative pitch error (or variation), adjacent pitch error, and effective profile error. *Double flank roll testing* provides information about tooth-to-tooth composite error, total composite error, radial runout and variation in the centre distance..

In the present work, analysis and comparison between total composite error and radial runout of the spur gear pairs finished by abrasive flow finishing (AFF) and pulsed electrochemical honing (PECH) processes and the near net-shape manufactured gear pairs by wire electric discharge machining (WEDM) process. It has been observed from the results that the Abrasive Flow Finishing of gears is more effective than Pulsed electrochemical honing of gears.

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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)
F_i''	Total composite error(µm)
f_i''	Tooth to tooth composite error(µm)
A	Pressure angle of the involute profile (degree)
I	Amount of current passed in the IEG (A)
V	Applied voltage (Volts)

Abbreviations

AMP	Advance Machining Processes
DOE	Design of Experiment
ECM	Electrochemical Machining
ECH	Electrochemical Honing
PECH	Pulsed Electrochemical Honing
AFM	Abrasive Flow Machining
AFF	Abrasive Flow Finishing
EDM	Electric Discharge Machining
WEDM	Wire Electric Discharge Machining
IEG	Inter Electrode Gap

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 Types 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 typical applicationthese gears.

1.2.1 According to position of axes of revolution

- **Cylindrical gears for parallel shafts:** Spur gears; and Helical (single, double, herringbone) gears. Figure 1.1 shows some typical applications of cylindrical 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)

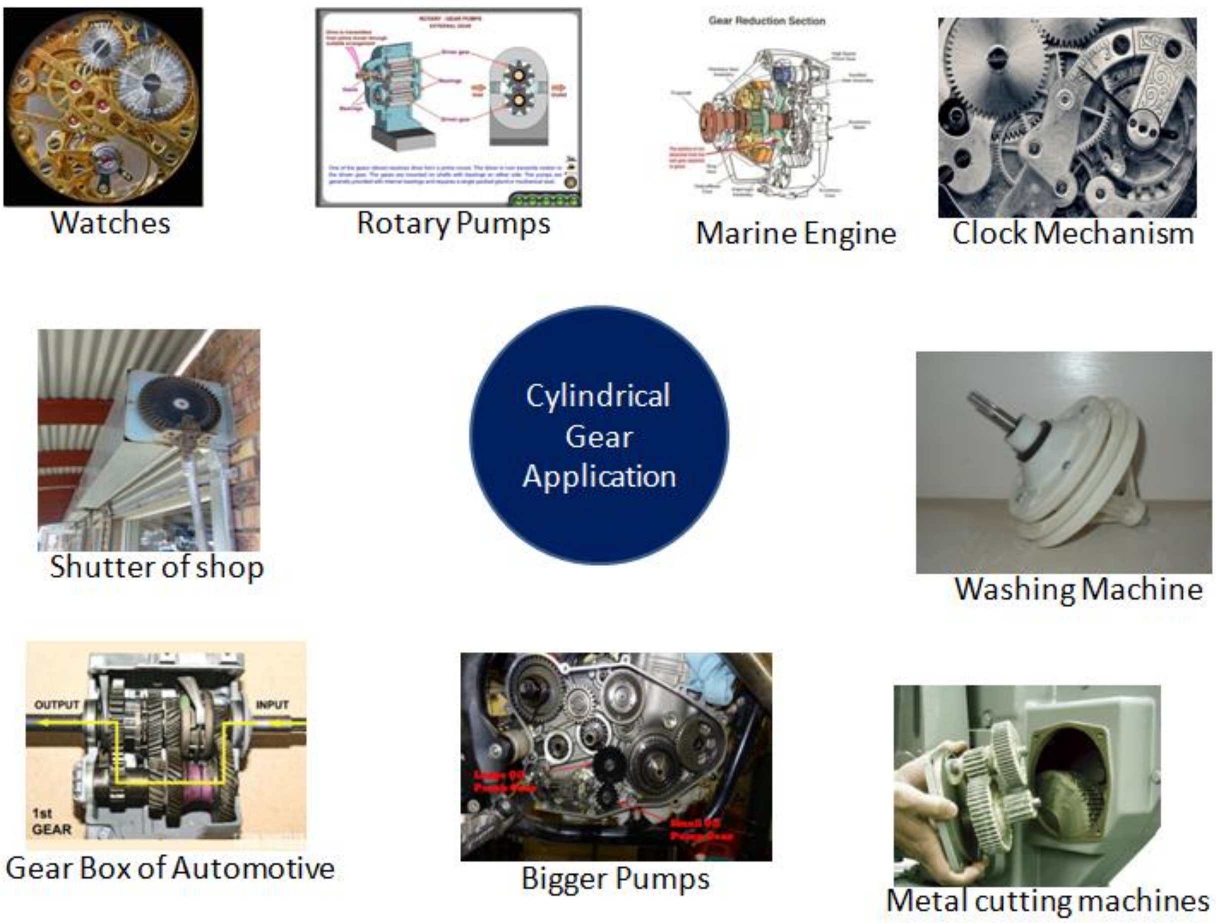


Fig. 1.1: Some typical applications of the cylindrical gears.

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 Introduction to Gear Inspection

Gears are one of the most commonly used devices for both engineering and non-engineering applications offering an elegant solution to the problem of effective power and/or motion transmission. Modern gear drive design must provide quiet and reliable performance at high power, which can only be achieved by using gears which have accurate geometry like of Involute helicoid system. Metrology or inspection of gears can be divided into two subareas functional testing and analytical testing as shown in Fig. 1.2. These two types of gear inspection provide fundamentally different information having their own advantages and disadvantages.

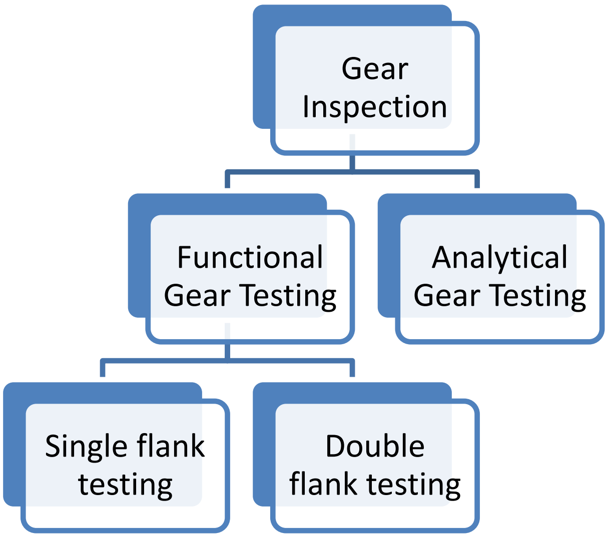


Fig. 1.2: Classification of inspection or metrology of gears.

Analytical testing of a gear determines different parameters describing its microgeometry such parameters describing form of its teeth (i.e. profile and lead), parameters describing location of its teeth (i.e. pitch and runout), and parameters describing topology of its teeth. It does not use any master or reference gear.

Functional testing of gears is qualitative test which determines whether the manufactured gear will have functional performance as intended or not i.e. it can be considered as an ***inspection by attributes***. It simulates the actual working conditions of the gears by rolling the manufactured gear with the reference or master gear and measuring the variation in centre distance. When two gears are in mesh with each other, any errors in tooth form, pitch and concentricity of pitch line causes variation in their center distance. According to method of contact between the rolling gears, functional testing can either be performed as single flank roll testing or double flank roll testing. Accordingly they provide different information. *Single flank roll testing* provides information about tooth-to-tooth transmission error, *profile conjugacy* (in terms of total transmission error), cumulative pitch error (or variation), adjacent pitch error, and effective profile error. *Double flank roll testing* provides information about tooth-to-tooth composite error, total composite error, radial runout and variation in the centre distance. A uniform variation in plot of center distance shows profile variation whereas a sudden jump on it indicates the pitch variations

1.5 Double Flank Roll Testing

Double flank roll testing is a valuable technique that can functionally provide quality control results of test gears quickly and easily during manufacturing. Its successful use requires careful planning of design of test gear and master gear and gage control methods in order to achieve the desired results in an application. It is used in the gear industry to identify potential manufacturing defects present in the gear. It is a faster and effective screening tool that can identify whether the gear manufacturing process has deviated from the ideal condition that could result in a loss of conjugate action, a change in backlash, or an unwanted gear noise.

Figure 1.3 shows working principle of the double flank roll testing apparatus. In this either the test gear or master gear of known precision is mounted in such a way that it is constrained from all motion other than rotary motion. The other gear is mounted on a floating slide mechanism that allows its rotation and movement along an axis between the line of centres of the master and test gear. A spring (with a preset force) pushes the floating slide, resulting in zero-backlash, double-flank contact (i.e., on both left and right flanks) between the test and master gears. As the master gear (or test gear) is rotated (by hand or by motor), the other gear follows. Involute theory dictates that perfectly formed teeth will prevent any movement of the floating slide between the line-of-centres. However, since no gear can be manufactured in absolutely perfect condition, there will always be some movement of the floating slide as the gears rotate. The magnitude of this movement is measured with either a mechanical indicator or electronic detector that contacts the slide mechanism. If the measuring instrument is calibrated to an actual distance reading between the centres of the gears, then an actual tight mesh centre distance result can be obtained.

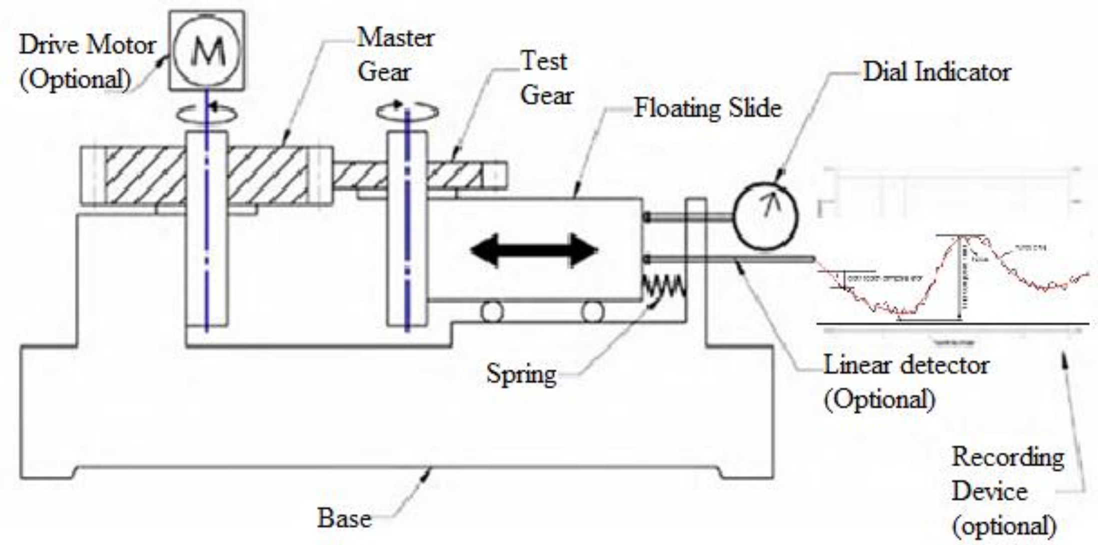


Fig 1.3: Working principle of double flank roll tester **(Reiter and Eberle, 2014)**.

In order to maintain accuracy, intimate double flank contact must be maintained throughout the measurement process. Therefore, selection of the pre-set spring force and the speed-of-rotation of the gears should be given careful consideration to limit measurement errors. In addition, if there is excessive resistance coming from the mounting of either the master gear on its mandrel or of the test gear on its mandrel, then a low, pre-set spring force will result in separation of the two gears out of double-flank contact, creating an error in the measured values. The correct pre-set spring force is the minimum force needed to maintain continuous, double flank contact without distorting the test gear. The speed of rotation of the gears should be selected by taking into account the natural response of the mechanical and electrical (if so equipped) elements of the equipment. The parameters that can be measured made on a double flank roll tester are shown in Figure 1.4 and are explained in the following sections.

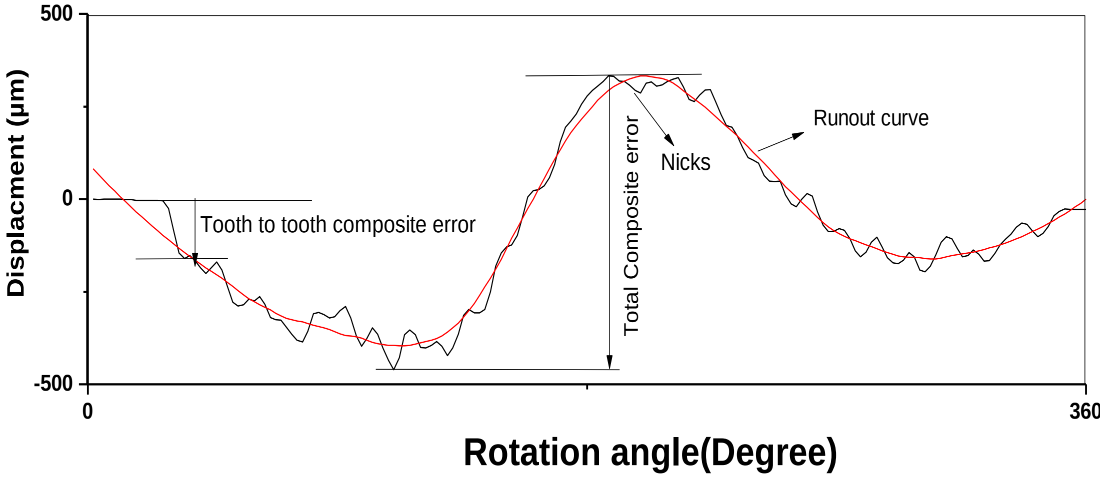


Fig. 1.4: Typical graph generated by double flank roll testing equipment.

1.5.1 Tooth-to-tooth Composite Error

Tooth-to-tooth composite error $\left(f_i''\right)$ is the variation in the centre distance as the test gear is rotated by amount equal to 360/N (no of teeth). It is defined as the greatest deviation indicator reading within a single, circular tooth pitch. It includes the effects of profile, pitch, tooth thickness and tooth alignment variations in both the work and master gears. It is based on the worst tooth on the entire gear. The gear tested in Figure 1.4 shows this to be in the zone around tooth 2. As the number of teeth in a gear becomes smaller, the ratio of the tooth-to-tooth error to total composite error generally increases. In the extreme condition, a single-start worm (i.e., one tooth) will have a tooth-to-tooth composite error equivalent to its total composite error. As the number of teeth increases, the tooth-to-tooth results are considered to be a better indicator of anomalies in the tooth pitch, profile and helix. Errors in gear pressure angle will result in a repeated pattern of arches. Use of tooth-to-tooth test limits also helps to control burrs and nicks in gears that are not always detected by analytical measurement techniques.

1.5.2 Total Composite Error (TCE)

Total composite error $(F_i^{''})$ is the total change in the centre distance in one complete revolution of the test gear i.e. difference between the maximum and minimum indicator (or linear detector) readings during one revolution of the test gear. It is the combination of runout with tooth-to-tooth composite variation. It is not possible to accurately establish the magnitude of each individual effect on the total composite error using the double flank roll testing. Hence, double flank roll testing is very good at screening the quality of gear production and flagging the potential errors, but its results may not identify the specific nature of the problem. Other tests such as analytical testing would need to be performed in to measure the value of runout error, errors in pitche, profiles and lead of the test gear.

1.5.3 Radial Runout

Radial runout (F_r) of the test gear is the difference between the maximum and the minimum radial distance from the gear axis as observed by removing the short-term or undulation pitch deviations and analysing the long-term sinusoidal wave form.

The norm ISO 1328: part-2 **(1998)** provides the maximum tolerance values for the total composite error $(F_i^{''})$, tooth-to-tooth composite error $(f_i^{''})$ and radial runout (F_r) in terms of module *m*; pitch diameter *d* and accuracy grade *Q* of the test gear. It comprises nine accuracy grades of which grade 4 is the highest and grade 12 is the lowest. Following are the relations which can be used for accuracy grade 5.

$$F_i^{''}(\mu m) = 3.2\, m + 1.01\sqrt{d} + 6.4 \qquad (1)$$

$$f_i^{''}(\mu m) = 2.96\, m + 0.01\sqrt{d} + 0.8 \qquad (2)$$

$$F_r(\mu m) = 0.24\, m + \sqrt{d} + 5.6 \qquad (3)$$

The corresponding values for higher or lower accuracy grades can be obtained multiplying by a factor of $2^{0.5(Q-5)}$ i.e. relation for total composite error for an accuracy grade Q takes following form:·

$$F_i^{''}(\mu m) = (3.2\, m + 1.01\sqrt{d} + 6.4\ )2^{0.5(Q-5)} \qquad (1a)$$

1.6 Single Flank Roll Testing

In **s**ingle flank roll testing, the test gear and master gear roll together at their proper centre distance with backlash and with only one flank in contact as depicted in Fig 1.5. This inspection process more closely simulates operation of the gears in their application. It can test mating gears in pairs or a test gear meshing with a master gear. The most important aspect of single flank roll testing is that it permits measurement of profile conjugacy through transmission error, which is the parameter that most closely relates to typical gear noise. Transmission error is the difference between the actual position of the output (or driven) gear and the position it would occupy if the gears were perfectly conjugate. It can be expressed in angular units as

$$Transmission\,error = \theta_2 - \theta_1 \frac{Z_1}{Z_2}\ (radians)$$

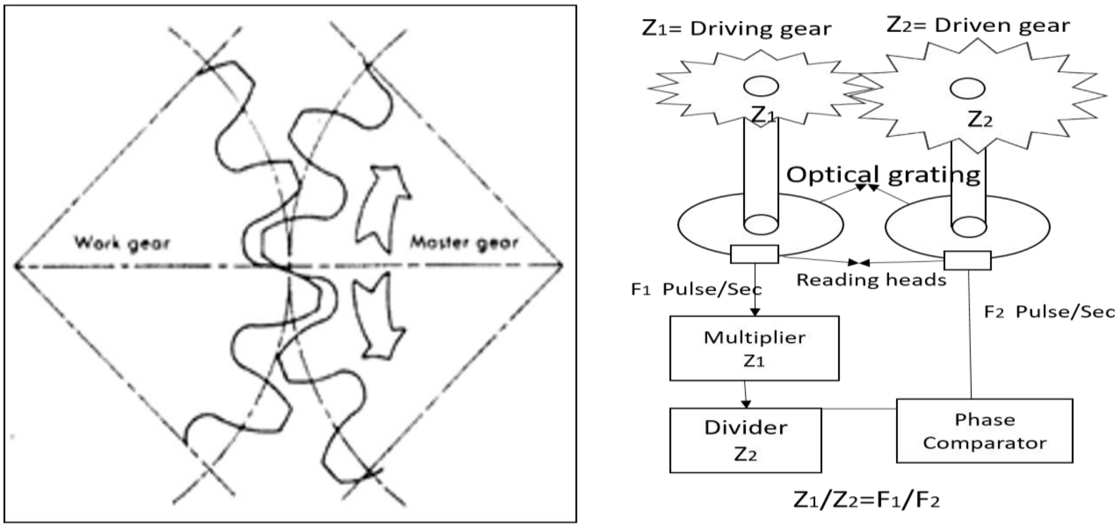


Fig. 1.5: Working principle of a typical single flank roll testing equipment.

The single flank roll tester runs using optical encoders or other devices to measure rotational motion (angular displacement error). Encoders may be attached to the input and output shafts of a special machine for testing pairs of gears. The encoders may also be used portably by attaching them directly to the input and output shafts of an actual gear box so as to inspect the quality of a complete train of gears. Data from the encoders is processed in an instrument that shows the accuracy or smoothness of rotational motion resulting from the meshing gears. This data can be directly related to portions of involute or profile errors, pitch variation, runout and accumulated pitch variation. The two motions which are to be compared are monitored by circular optical gratings. Each grating produces a train of pulses having a frequency which is a measure of the angular movement of each corresponding shaft and hence the gear mounted on it. The pulse frequency for each grating is usually different when gear ratio is not equal to 1. Ratio of pulse frequencies of two shafts is equal to ratio of number of teeth of the gears mounted on them (i.e. $F_2 = F_1 \times Z_1 / Z_2$). However, F_2 has superimposed on it a frequency modulation due to transmission errors of the gears under test. Therefore, the pulse train coming from the grating on shaft 2 will have small differences in phase from the pulse train for shaft 1. This phase difference between the two represents the amount of error in the gears being tested. Phase differences of less than one arc second can be detected. This difference is recorded as an analogue waveform and comes out of the instrument on a strip chart as shown in Figure 1.6. Gears with perfect involute tooth forms will roll together with uniform motion. When pitch errors or involute modifications (intentional or otherwise) exist in a gear, non-uniform motion or transmission errors will result.

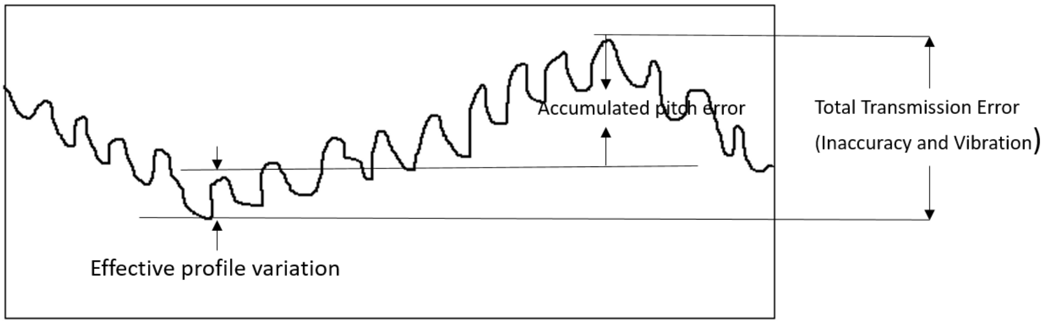


Fig 1.6: Interpretation of the results from the single flank roll testing.

Figure 1.7 depicts direct relationship between involute shape and the graph recorded by a single flank roll tester. Such graphs represent some typical non-uniform motion that gears are likely to transmit that creates the exciting force that will shake a structure and cause noise.

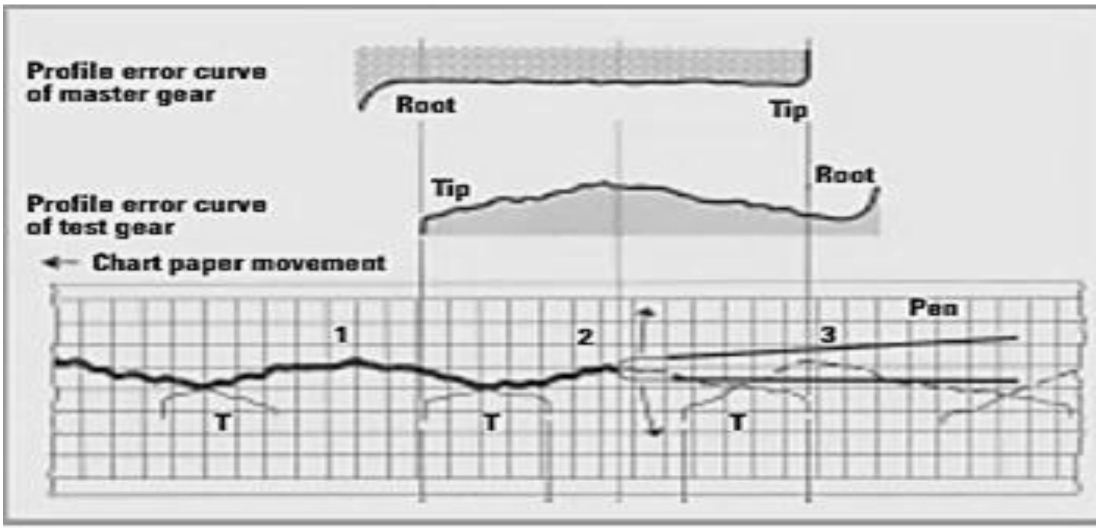
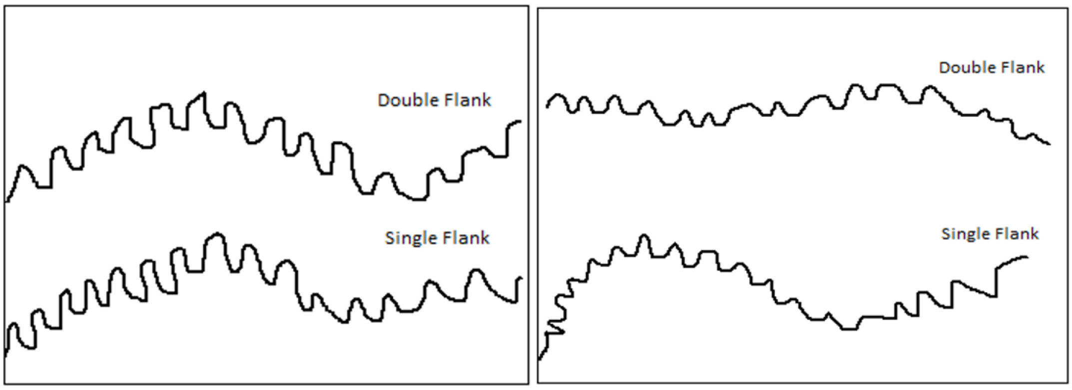


Fig.1.7: Direct relationship between an involute tooth and a single flank graph.

The ability to detect the cumulative pitch error is an important capability of single flank roll testing. A gear with runout does have cumulative pitch error whereas a gear with cumulative pitch error may not necessarily have runout. A gear can be manufactured by various means without having any runout but could have large accumulative pitch error. This can happen when a gear is hobbed and then shaved or ground on a machine that does not have a rigid drive which couples the tool to the workpiece. When the gear is hobbed with an eccentric pitch circle, the slots are at different radii and angular positions. When the gear is shaved, it is run with a tool that maintains a constant, rigid centre distance, but is not connected to the workpiece by a drive train. Therefore, all slots are now machined to the same radius, from the centre of rotation and are displaced from true angular position by varying small amounts. The resulting gear has very small amounts of individual pitch errors but, has a large cumulative pitch error which can be detected by the single flank roll tester. Accumulative pitch error imparts a gear all the undesirable effects associated with the runout. Such gear will be check as of ‘good quality’ by both analytical testing and double flank roll tester. Cumulative pitch error of gear not having runout can only be found or properly evaluated either by a single flank roll tester or by a precision index/single probe spacing checker. Fig. 1.8 illustrates the advantages of single flank roll testing over double flank roll testing.



(a) **(b)**

Fig 1.8: Typical recording by single and double flank roll testers for a gear having (a) runout and consequently cumulative pitch error; and (b) cumulative pitch error but no runout.

1.7 Comparison of Single Flank and Double Flank Roll Testing

- Single flank roll testing provides observations (analytical or functional) of gear geometric quality involving only one flank at a time. The data provided is tangential rather than radial in direction, thereby offering information about the way the gear operates an advantage over double flank roll testing.
- Double flank test data can reveal radial eccentricity or out-of-roundness errors that can produce gear transmission error. It cannot reveal angular tooth position errors which also produce transmission errors.
- Double flank roll tester can detect non-systematic errors such as nicks, burrs or hard spots.

1.8 Organization of Thesis

- **Chapter 2** presents review of the past work on metrology of gears and double flank roll testing of gears, research objectives defined to bridge the identified research gaps and research methodology used in the present work.
- **Chapter 3** describes design and development of double flank gear roll tester to study the total composite error, total runout error, tooth-to-tooth composite error of the spur gears along with details of the subsystems of the developed apparatus.
- **Chapter 4** presents results/reports on planning and details of measurements for getting total composite error and total runout error of the unfinished and finished gear by PECH and abrasive flow finishing (AFF) processes and near net-shape manufactured spur gears by WEDM..
- **Chapter 5** highlights the conclusions of the present work and scope for future work based on the limitations of the present work.

Chapter 2

Review and Past Work

This chapter deals with the detail explanation of relevant theories and reviewed literature on gear metrology and specifically functional testing of gears and later on some work will be discussed on optimization of WEDM parameters for minimization of micro geometrical errors in the gears.

2.1 Past Work on Functional Testing of Gears

Goch (2003) presented a comprehensive review of gear metrology mentioning that tactile probing methods are dominant. He described new modelling and measuring principles, enabling a superficial description and inspection of gears especially optical measuring methods, inspection of the micro-gears and alignment problems. He also reported about actual accuracy limits of gear measurements and pointed out that significant reduction in the measuring uncertainty associated with gears, standards and instruments is an urgent need for production of high precision gears.

Reiter and Eberle (2014) described the theory of double flank roll inspection, detailing the apparatus used, various measurements that can be achieved using it, the calculations involved and their interpretation, discussion of the practical applications of double flank roll testing especially for large-volume operations. They also addressed statistical techniques that can be used in conjunction with double flank roll testing.

Cacho et al. (2013) studied and analysed the existing verification techniques for micro-gears along with the details of double flank gear roll tester for these gear. They concluded that use of double flank gear roll testing as verification technique for micro-gears is feasible.

Pueo et al. (2015) presented development of universal roll testing apparatus which combines single flank and double flank roll testing for worm-worm gear. Their obtained results allow development of a traceable calibration procedure to establish measurement uncertainty for gear roll testers.

2.2 Past Work on Near Net-shape Manufacturing of Gear by WEDM

Gupta and Jain (2014) reported about the analysis and optimization of micro-geometry parameters (i.e. total profile deviation ‘Fa’ and accumulated pitch deviation ‘Fp’) of the wire electric discharge machined for 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 micro-geometry 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 are 9V for voltage, 0.6 s for pulse-on time, 160 s for pulse-off time and 13 m/min for wire feed rate having DIN quality number as 7 and 5 respectively for profile and pitch.

2.3 Identified Research Gaps

- No work has been reported on development of double flank gear roll tester for the macro-sized spur gear.
- No analysis and comparison has been done on the basis of total composite error in the spur gears finished by different advanced finishing processes.

2.4 Objectives of the Present Research Work

- Design and development of dual flank gear roll tester for macro-sized cylindrical gears.
- To analyse and compare the total composite error and radial runout of the spur gear pairs finished by abrasive flow finishing (AFF) and pulsed electrochemical honing (PECH) processes and the near net-shape manufactured gear pairs by wire electric discharge machining (WEDM) process.

Chapter 3

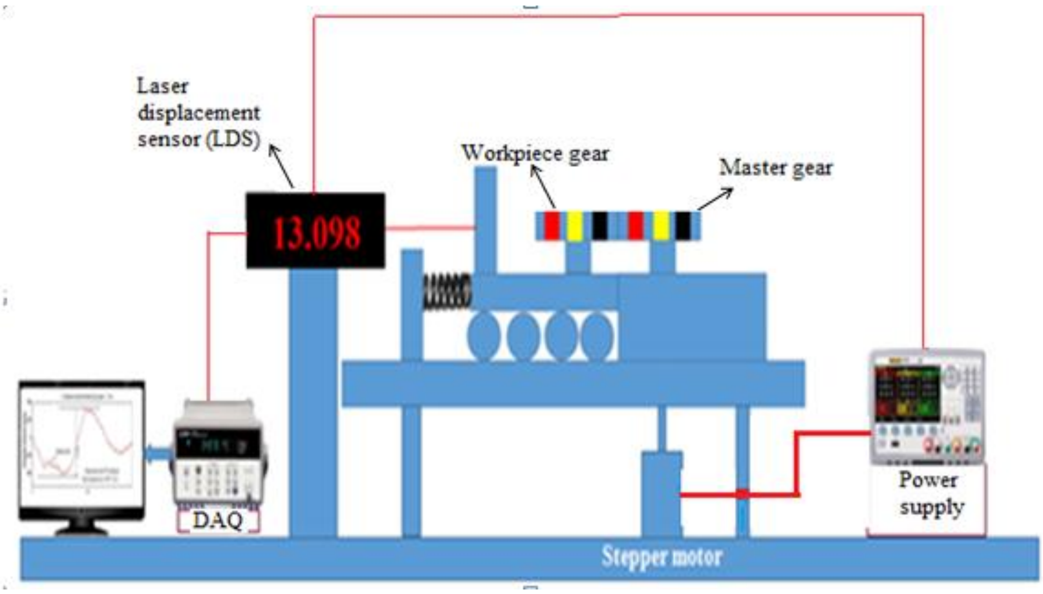
Development of Double Flank Tester

Details of different components of the double flank roll tester for the cylindrical gears are described in this chapter. It was manufactured at Central Workshop of IIT Indore using different operations such as drilling, tapping, milling, gas cutting, and welding, boring, turning on the corresponding machine. It required 500 hours of machining. Dimensions of the apparatus are 300 mm x 500 mm x12 mm with frame height being 250 mm and the material of base plate is mild steel. Slide plate and base plates were joined by nuts and bolts to the linear motion guide and frame structure respectively.

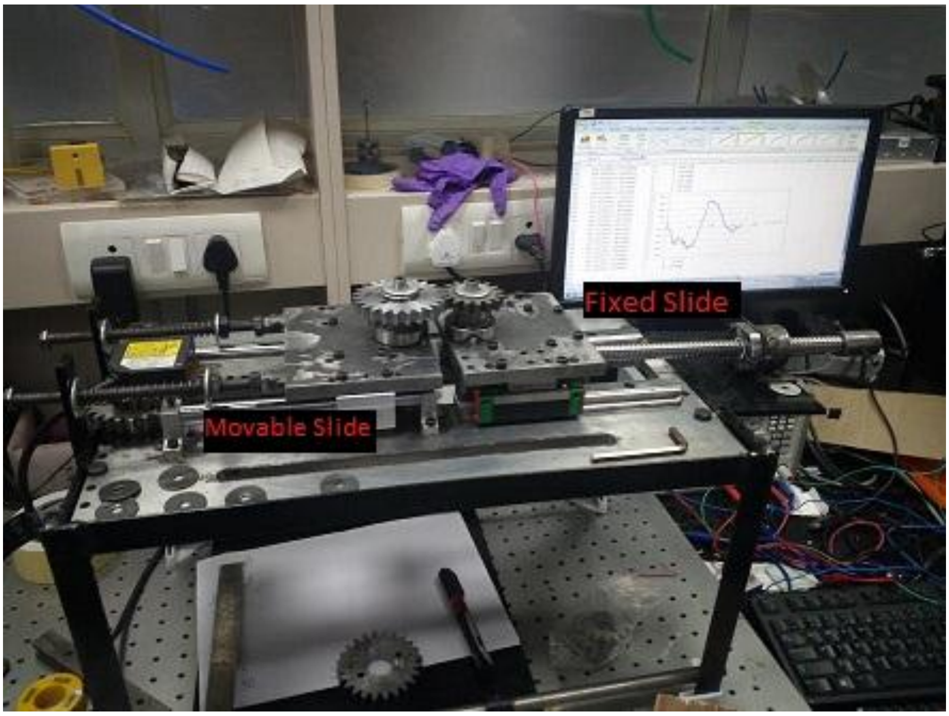
3.1 Development of the Double Flank Tester for Cylindrical Gears

Figure 3.1 depicts the schematic diagram (Fig. 3.1a) and photograph (Fig. 3.1b) of the double flank roll tester for the cylindrical gears. Its major subparts are:

- Frame structure
- Base plate
- Measuring instruments which includes laser displacement sensor
- Linear motion guide bearing
- Ball screw
- Slide plates
- Helical spring



(a)



(b)

Fig. 3.1: The developed double flank roll tester for cylindrical gears: (a) schematic diagram; (b) photograph.

The developed double flank roll tester had following components:

- **Frame:** Mild steel angle of 3 mm was used to make the structure of the supporting frame (shown in Fig. 3.2) having dimensions 520 mm x 320 mm x 250 mm and joined by electric arc welding. Base plate is bolted in the frame structure and frame structure was painted by black oil paint to prevent from corrosion and for aesthetic purpose.

Fig 3.2: Frame structure.

- **Linear motion guide:** Linear motion guide (Fig. 3.3) was attached to the base plate so that the sliding plate can slide over the guide ways smoothly. While attaching these guide ways special attention was given to maintain the parallelism of these guide ways for smooth sliding motion.

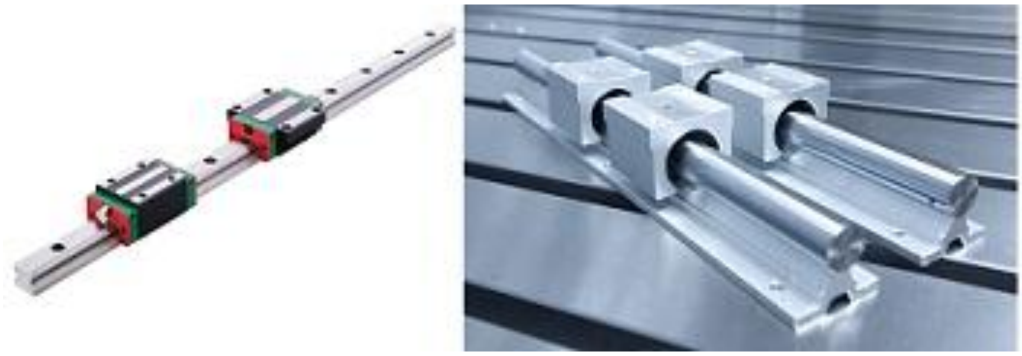


Fig 3.3: Linear motion guide.

- **Ball Screw:** For making one slide plate fixed, 16 mm ball screw made of high carbon steel of pitch 2.5 mm (Fig. 3.4) was attached to the base of slide plate with the help of pedestal bearing and at other end it is held fixed with 5 mm bolts to the frame structure so that the slide plate can be fixed or can move as per the requirement.

Fig 3.4: Ball screw.

- **Stepper motor:** Fixed slide consisting of a shaft was connected to a stepper motor (Fig 3.5) having 4.5 kg-cm torque capacity through flexible coupling. Stepper motor is connected to the motor driver L298N which is controlled by Aurdino uno controller.

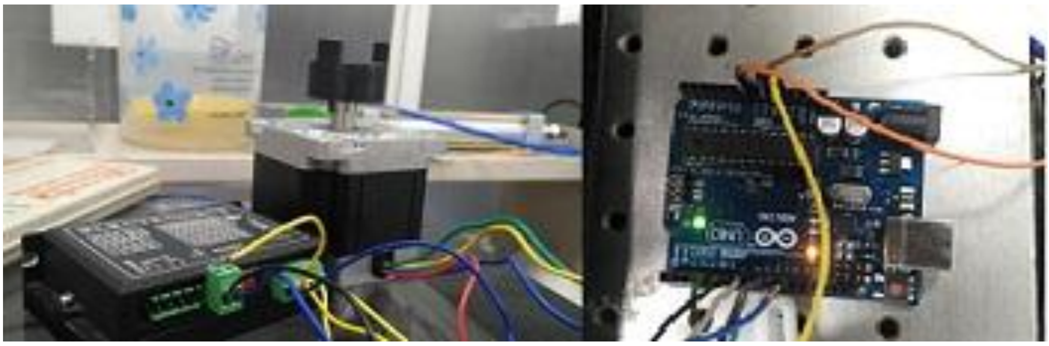


Fig 3.5: Stepper motor, its driver and controller.

Aurdino Controller and its Coding for Stepper Motor

```
int d= 50;
void apparatus () {
pinMode(8, OUTPUT);
pinMode( 9, OUTPUT);
pinMode( 10, OUTPUT);
pinMode ( 11, OUTPUT);
```

```
pinMode ( 5,OUTPUT);
pinMode ( 6, OUTPUT);
// put your apparatus  code here, to run once:

}
void loop() {
  // put your main code here, to run repeatedly:
analogWrite ( 5, 127);
analogWrite( 6, 127);
digitalWrite ( 8, HIGH);
digitalWrite ( 9, LOW);
digitalWrite ( 10, LOW);
digitalWrite ( 11, LOW);
delay( d);
digitalWrite ( 8, LOW);
digitalWrite ( 9, HIGH);
digitalWrite ( 10, LOW);
digitalWrite ( 11, LOW);
delay( d);

digitalWrite ( 8, LOW);
digitalWrite ( 9, LOW);
digitalWrite ( 10, HIGH);
digitalWrite ( 11, LOW);
delay( d);

digitalWrite ( 8, LOW);
digitalWrite ( 9, LOW);
digitalWrite ( 10, LOW);
digitalWrite ( 11, HIGH);
delay( d);
}
```

- **Helical Spring:** Helical spring was used to provide constant force to ensure double flank contact throughout the rotation of the gear. Two helical springs of 150 mm length and 11 mm Inner diameter (Fig. 3.6a) were attached to the floating slide. Stiffness of the spring was measured on the universal testing machine.


(a)


(b)


(c)

Fig. 3.6: (a) Helical springs used in apparatus (b) fixture used to measure stiffness of spring (c) compression of spring on universal testing machine.

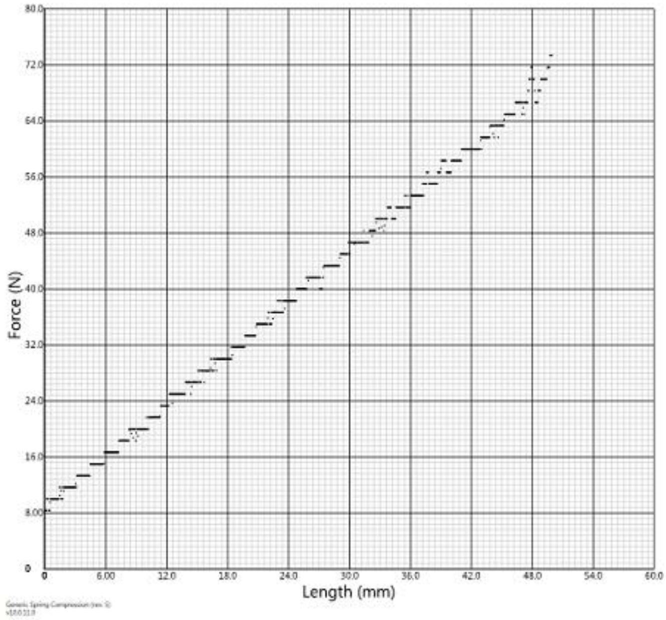
Measurement of Spring Stiffness: For an elastic body with a single degree of freedom (DOF) for example stretching or compression, the stiffness is defined as is the displacement produced by the force along the same degree of freedom (for instance, the change in length of a stretched spring).

Hence, Stiffness of the spring (K) can be written as,

$$\mathbf{K = F/d} \text{ (N/mm)}$$

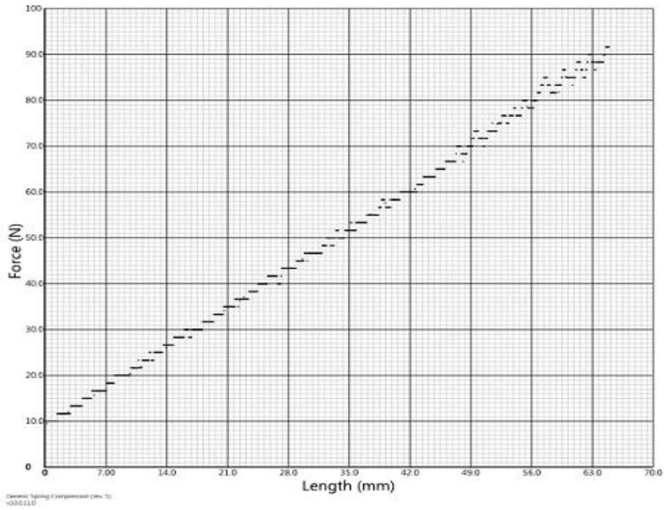
Where, d is deflection produced in a spring due to load applied F.

The stiffness of spring was measured using a specially designed fixture made of metalon (Fig. 3.6b) which contains one male and one female part. Spring is mounted on the fixture and then whole fixture is mounted on UTM (shown in Fig 3.6c) and then spring is compressed up to 50 mm. This experiment was performed three times to get an average value of the spring stiffness i.e. 1.203 N/mm.



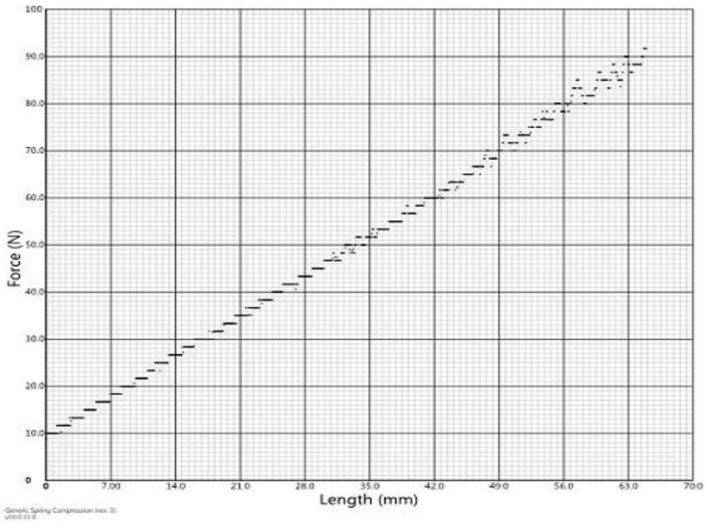
Stiffness obtained:
1.23 N/mm

(a)



Stiffness obtained:
1.19 N/mm

(b)



Stiffness obtained:
1.19 N/mm

(c)

Fig.3.7: Results of measurement of spring stiffness performed on UTM (a) experiment no 1 (b) experiment no 2 (c) experiment no 3.

Since, the spring length is 150 mm, and the stiffness measured is 1.203 N/mm for this length but due to modification in apparatus, the length of spring was reduced to 90 mm. Therefore, according to the relation for diving helical spring into different parts if the stiffness of spring is K_{spring}, then,

$$K_{new} = \frac{M+N}{N} K_{spring}$$

Where, M = 90 mm and N = 60 mm giving **K_{new} = 3.0075 (N/mm).**

Therefore, for the calculation of pre-setting force, the pre-set force may be needed to be selected specifically for the design of the test gear design and the correct pre-set spring force is the minimum force needed to maintain continuous, double flank contact without distorting the test gear. For the test gears which have been used in double flank roll testing, spring compression is found to be 3 mm to make sure the gear pair is in double flank contact. Therefore spring pre-set force is,

F_{spring}= (2*K_{new})*3 N =18.045 N

3.2 Details of Manufacturing and Finishing of 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 3.8a and 3.8b 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

The test gears are manufactured by gear hobbing machine. Prior to that gear blanks of external diameter of 78 mm are manufactured on lathe machine from alloy steel cylindrical bar of 90 mm diameter. These blanks are than bored to 25.4 mm internal diameter. These blanks are mounted on gear hobbing machine for hobbing operation. The manufactured spur gear are then finished by two advance finishing process namely

PECH and AFF by my co-researcher Gaurav Kumar. These finished gears are used as a test gears to calculate their total composite error and total runout error by the developed double flank gear roll tester. Similarly pinion gears are manufactured by gear hobbing machine and pinion gear blanks of diameter 54 mm are manufactured on lathe machine from alloy steel cylindrical bar of diameter 65 mm.

Gear Hobbing: It is a machining process in which gear teeth are progressively generated by a series of cuts using hob as a cutting tool which has serrated cutting edges. Hob and gear blank rotate continuously by a proper gearing as shown in Fig.3.7 to cut gear teeth. Simultaneously, the rotating hob is fed inward until the desired tooth depth is achieved, then cutting continues until the entire gear is finished. Machines for cutting precision gears are generally CNC type and are often housed in the air-conditioned rooms to avoid dimensional deformations.

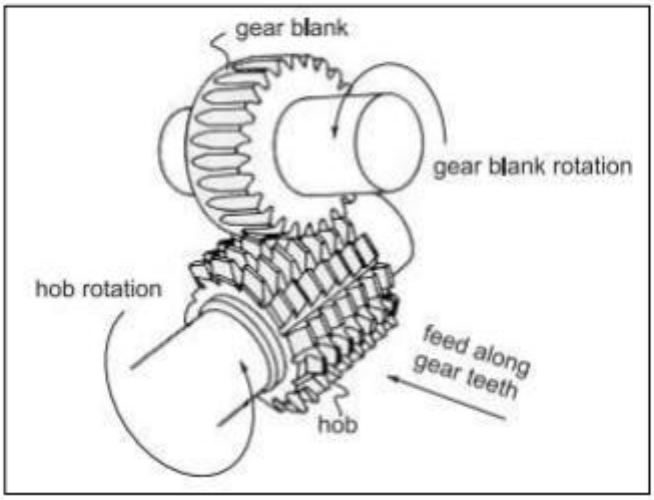
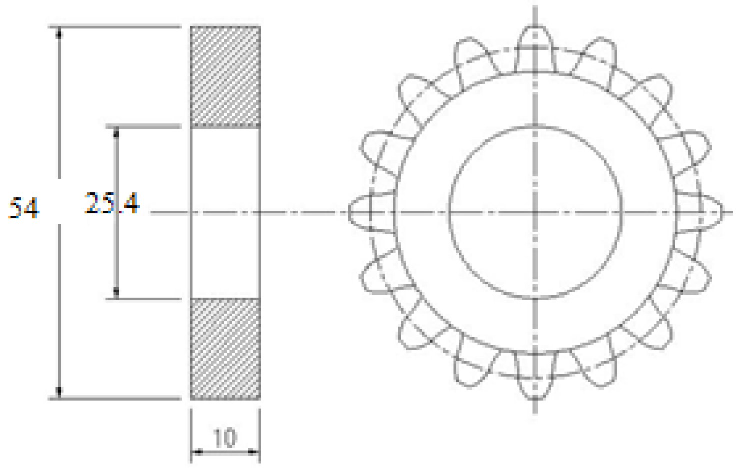
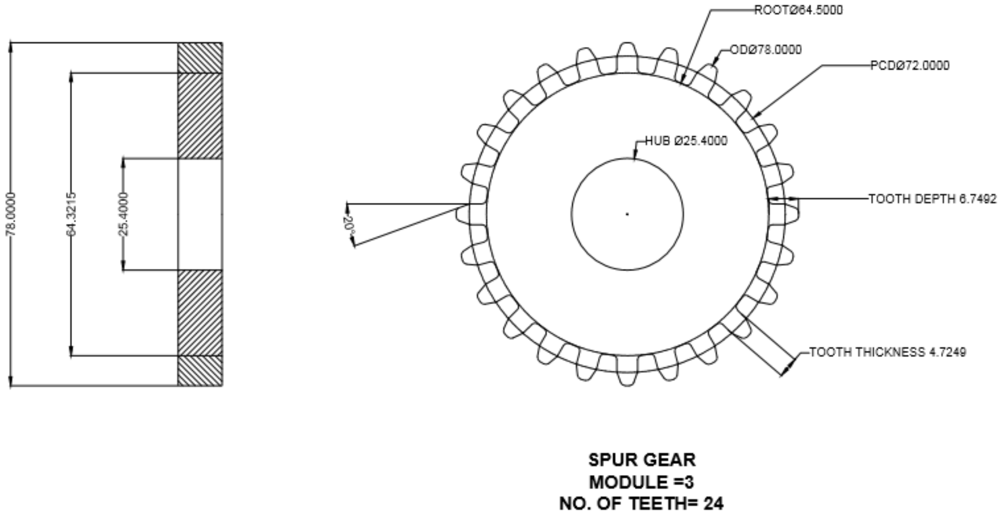


Fig. 3.8: Principle of cutting teeth by hobbing operation.



(a)



(b)

Fig. 3.9: Drawing of (a) pinion; (b) workpiece gear.

3.3 Fabrication of the Master Gear

Master gears are required for single and double flank roll testing. They are subjected to wear and damage and must be recalibrated periodically. Master gear calibration reports are required by ANSI/AGMA 2015-1-A01 to include statements of measurement conditions and the measurement uncertainty for each parameter reported. For accuracy tolerance purposes, master gears are simply defined in ANSI/AGMA 2015-1-A01 as those gears meeting accuracy grade 4 and better. Minimum master gear accuracy grades are recommended for test gear accuracy grades, as shown in table 3.2. Properly calibrated master gears can provide an attractive reference for calibration of elemental gear measuring instruments.

3.3.1 Design Considerations for Master Gear

Master gears used in double-flank composite measurements must meet the following criteria in order to mesh properly with a test gear.

- The tip of the master gear must not contact the test gear below the form diameter of the test gear. This applies to initial contact and to any type of secondary contact in the fillet zone due to inadequate clearance.
- The tip of the test gear must not contact the master gear below the form diameter of the master gear. This applies to initial contact and to any type of secondary contact in the fillet zone due to inadequate clearance.
- The minimum contact ratio of the double-flank test must not be less than 1.0 when accounting for maximum tooth thickness, minimum outside diameter, maximum root diameter and maximum tip radius of the test gear. Should the contact ratio drop below 1.0, the meshing action of the gears on test will generate an immediate jump

in the double-flank result for every tooth meshing cycle. This happens when the spring of the slide on the composite tester compensates for the loss of mesh force by abruptly pushing the gears together.

- The maximum contact ratio of the double-flank test should be less than 2 when taking into account minimum tooth thickness, maximum outside diameter, minimum root diameter, and minimum tip radius of the test gear. High contact ratios on the double-flank tester promote more overlapping of the mesh and may hide errors in the test gear that may otherwise exist. Helical gears, due to their face widths, may have an overall contact ratio greater than 2.0 when run against a master gear covering its full face width. In such cases a decision should be made to either accept the possible smoothing out of errors that would result with this high contact ratio, or to possibly reduce the face width of the master gear and measure the helical gear in different contact zones along the test gear's axis while maintaining an overall contact ratio of less than 2.

Table.3.2: Selection of grade for the master gear.

Master Gear Grades	Test Gear Grades
Grade 2	Grade 4-5
Grade 3	Grade 6-7
Grade 4	Grade 8 and Higher

Gear of such a high grade can be manufactured with conventional machining (Gear hobbing, Gear shaping) followed by advanced finishing operation to get best quality gear, but in recent years so much work has been reported on the gears manufactured by WEDM. **Gupta *et al.*2014** has worked on the optimization of WEDM parameter for minimizing the total profile and accumulated pitch deviations for miniature gears of brass and reported the optimized values of profile (11.5 μm) and pitch (9.1 μm) categorize the gear in DIN quality number **7** and **5** respectively, which are superior than other existing conventional processes for miniature gear manufacturing. But, for the present work the gear is a macro-gear and material is alloy steel of grade 20MnCr5 the need is to get optimized WEDM parameter for minimization of total profile error, accumulated pitch deviation, total lead deviation.

3.3.2 Planning and Details of Experiments

According to the research objective, experiments were planned by using statistical approach of design of experiments. Taguchi L_9 array was used to design the experiments by varying three input parameters at three levels each. Voltage, pulse-on time, pulse-off time while concerned parameters of micro-geometry, were chosen as performance measure of spur gears manufactured by WEDM process.

Design of experiments is a systematic method to determine the relationship between factors affecting a process and the output of that process. In other words, it is used to find cause-and-effect relationships. This information is needed to manage process inputs in order to optimize the output. Following are the major approaches to DOE.

Full Factorial Design: A full factorial experiment is an experiment whose design consists of two or more factors, each with a discrete possible level and whose experimental units take all possible combinations of all those levels across all such factors. Such an experiment allows studying the effect of each factor on the response variable, as well as on the effects of interactions between factors on the response variable. A common experimental design is the one with all input factors set at two levels each. If there are k factors each at 2 levels; a full factorial design has 2k runs. Thus for 6 factors at two levels it would take 64 trial runs.

Taguchi Method: The Full Factorial Design requires a large number of experiments to be carried out as stated above. It becomes laborious and complex, if the number of factors increase. To overcome this problem Taguchi suggested a specially designed method called the use of orthogonal array to study the entire parameter space with lesser number of experiments to be conducted. Taguchi thus, recommends the use of the loss function to measure the performance characteristics that are deviating from the desired target value. The value of this loss function is further transformed into signal-to-noise (S/N) ratio. It distinguishes between controllable variables and the variables that cannot be controlled and are referred as noise variables. It focuses on whether the variability is most influenced by the main effects, by interactions or by curvature by using signal-to-noise ratios (SN) to measure performance of a process or product. There are three types of S/N ratio (i) smaller-the-better: to be used when the response is to be minimized; (ii) larger-the-better: to be used then the response is to be maximized; and (iii) nominal-the-best: to be used when a target value is sought for the response.

3.3.3 Details of experiments

For the parametric optimization of the micro geometry responses in wire EDM, Taguchi method is selected. Three factors (voltage, pulse-on time and pulse-off time) with three different levels are selected as control variables while current, wire feed and wire tension are kept constant. Taguchi design permit to carry out 9 (L_9) experiments at different factor level combinations. The responses namely total profile error, total lead error and cumulative pitch error are recorded for each run .Table 1 shown below shows the readings observed during experiment for the three responses. As the lowest values of total profile error, total lead error and cumulative pith error are important for good quality of gear from wire EDM that's why "smaller is better" is chosen as quality characteristics.

Table.3.3: Details of variable and fixed input parameters used during experiments.

S. No.	Process parameters	Value	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	04	m/min
06	Wire tension	1.3	kg

3.4 Experimentation and Measurements

The gears blank were prepared from alloy steel of grade 20MnCr5 cylindrical bar of 70mm diameter and cut into pieces of 15mm thickness from power saw .They were made into a 10mm thick flat blank by facing operation on lathe machine. For measuring flatness of a blank, dial gauge indicator of least count 2µm was used. The deviation observed was in a range of 100-200 microns. These surface deviations were minimized by surface grinding operation up to 2-5 µm. The Gears were manufactured using Sprintcut CNC wire EDM machine using half-hard brass wire of 0.25 mm diameter and deionized water as dielectric.

Micro-geometry of the spur was inspected in terms of their form errors [i.e. total profile error (Fa), total lead error (Fb)] and location errors [i.e. cumulative pitch error (Fp), and total runout (Fr)]. Deutsche Normen (DIN) and American Gear Manufacturers Association (AGMA) are the universally accepted standards for denoting quality of the gears in terms of micro-geometry aspects. Lower DIN number or higher AGMA number indicates better quality of the gears and vice-versa. Considered parameters of micro geometry were measured on right hand and left hand flanks of tooth of the gears on the computer numeral controlled (CNC) gear metrology machine ***Smart-Gear*** from ***Wenzel Gear-Tec***, Germany.

Table.3.4: Results of experiments for the micro-geometry parameters

				Micro geometry			
S.No.	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	Run our error (Fr) 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	53.6	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

Fixed parameters: Wire material: brass; wire diameter: 0.25 mm; wire tension: 1300 g; deionised water; dielectric conductivity: 20μs/cm**.**

Gear specification: Material: alloy steel (20MnCr5); profile: Involute; type: external spur gear; pressure angle: 20 degree; module: 3 mm; no of teeth: 16; face width: 10 mm Table 3.5 shows the signal to noise ratio for three responses at different running condition. The main plots drawn and response table obtained from taguchi analysis for mean signal to noise ratio and means clearly shows the optimum level of factor combitation for each respones.

Table.3.5: Values of S/N Ratio corresponding to input and output parameters

Exp. No	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	S/N Ratio		
							F_a	F_p	F_b
1	12	0.6	39.5	67.3	36.0	171.3	-36.5603	-44.6751	-31.1261
2	12	0.8	44.5	59.8	7.0	208.6	-35.5340	-46.3863	-16.9020
3	**12**	**1.0**	**49.5**	**47.0**	**3.8**	**60.0**	**-33.4420**	**-35.5630**	**-11.5957**
4	16	0.6	44.5	57.9	32.7	119.2	-35.2536	-41.5255	-30.2910
5	16	0.8	49.5	53.6	4.1	64.3	-34.5833	-36.1642	-12.2557
6	16	1.0	39.5	65.0	10.1	60.9	-36.2583	-35.6923	-20.0864
7	20	0.6	49.5	69.5	8.3	184.7	-36.8397	-45.3293	-18.3816
8	20	0.8	39.5	72.5	29.2	233.5	-37.2068	-47.3657	-29.3077
9	20	1.0	44.5	71.5	27.0	176.6	-37.0861	-44.9398	-28.6273

As mean S/N ratio for total profile error (F_a) of, voltage is highest at level 1 and for pulse on time it is highest at level 3 and for pulse off time it is highest at level 3 (Fig.3.9). So for getting minimum value of total profile error the optimum levels for factors are 1,3,3 respectively i.e. optimum values of volage, pulse-on time, pulse-off time are,

V=12v , Ton=1µs , Toff=49.5 µs.

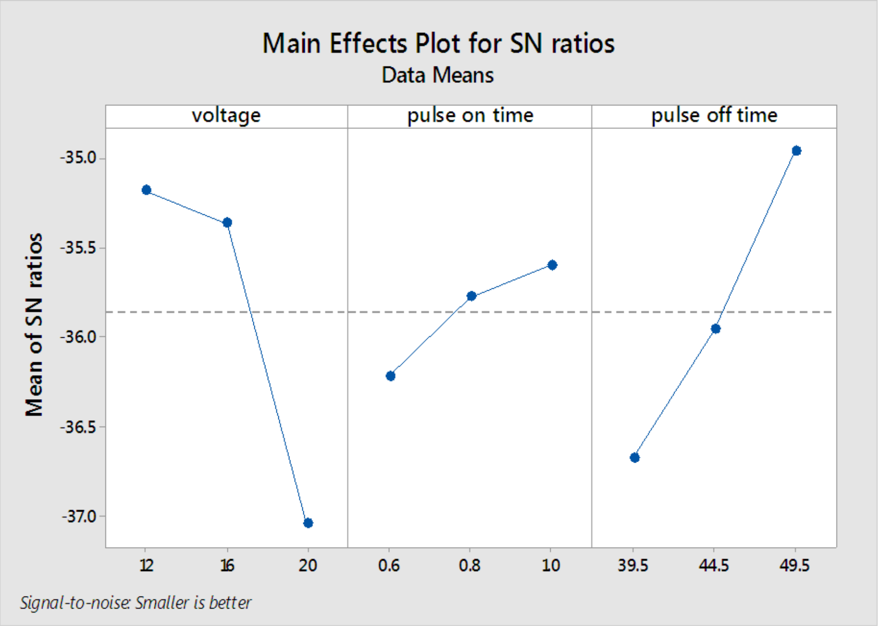


Fig. 3.10: Plot of S/N ratio for total profile error (F_a).

Similarly for mean S/N ratio for total lead error (F_b), voltage is highest at level 1 and for pulse on time it is highet at level 2 and for pulse off time it is highest at level 3 (Fig.3.10) So for getting minimum value of total lead error (F_b) the optimum levels for factors are 1,2,3 respectively, i.e. Optimum values of volage, pulse-on time, pulse-off time are

V = 12v , T_{on} = 0.8µs, T_{off} = 49.5µs.

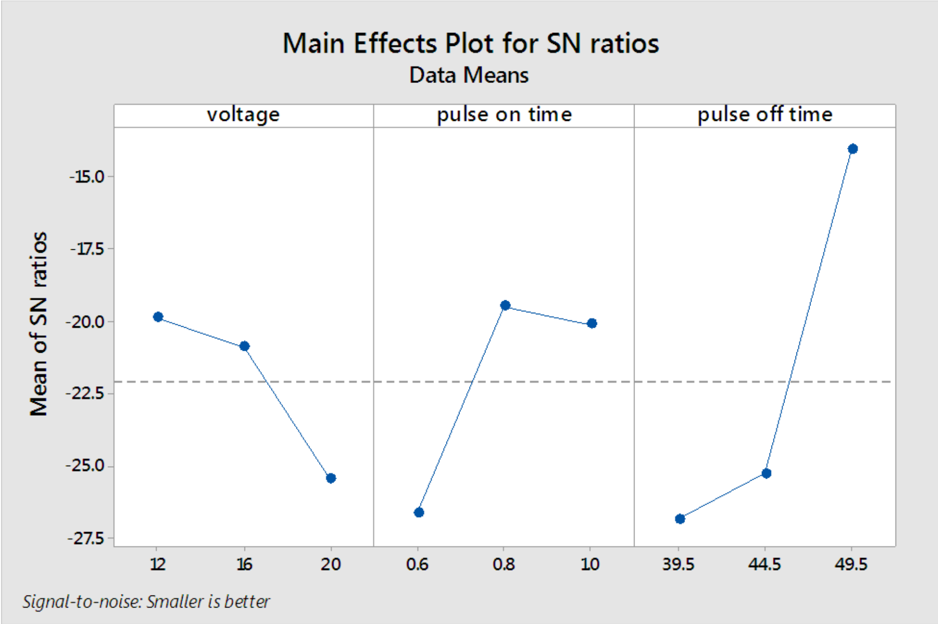


Fig. 3.11: Plot of S/N ratio for total lead error (F_b).

For mean S/N ratio for cumulative pitch error of (F_p). voltage is highest at level 2 and for pulse-on time it is highet at level 3 and for pulse-off time it is highest at level 3 (Fig 3.11). So for getting minimum value of cumulative pitch error the optimum levels for factors are 2,3,3 respectively, i.e. Optimum values of volage, pulse-on time, pulse-off time are

V = 16v , T_{on} = 1μs, T_{off} = 49.5μs

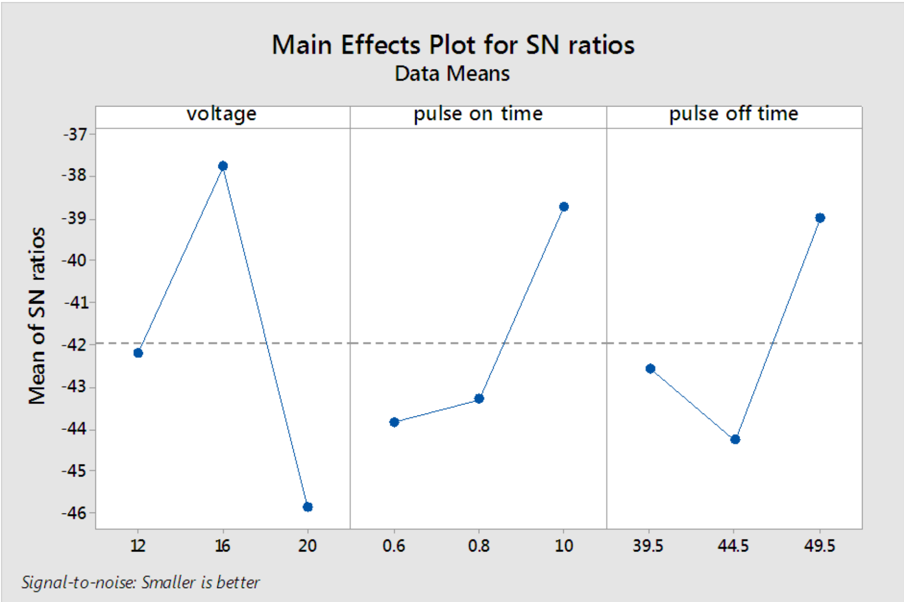


Fig. 3.12: Plot of S/N ratio for cumulative pitch error (F_p).

This analysis shows that the optimised input parameters for minimisation of total profile error (Fa) are **V=12v, Ton=1μs , Toff=49.5μs** and for cumulative pitch and lead error are **V=12v , Ton=0.8μs, Toff=49.5μs; V=16v , Ton=1μs, Toff=49.5μs** respectively i.e. the optimised parameters are different for F_a, F_b and F_p therefore on the basis of above analysis it would be difficult to report a unique optimised parameter, but from the observation of results of all nine experiments, experiment no 3 is shows the minimum micro geometry errors (F_a,F_b,F_p) out of all nine experiments therfore the parameters of experiment no 3 can be selected as best quality gear.

Gear no 3 can be selected for best quality gear and can be used as a master gear for finding out the Total composite error using Doublel flank gear roll tester.

Chapter 4

Results and Discussion

4.1 Procedure for Measurement on Double Flank Roll Tester

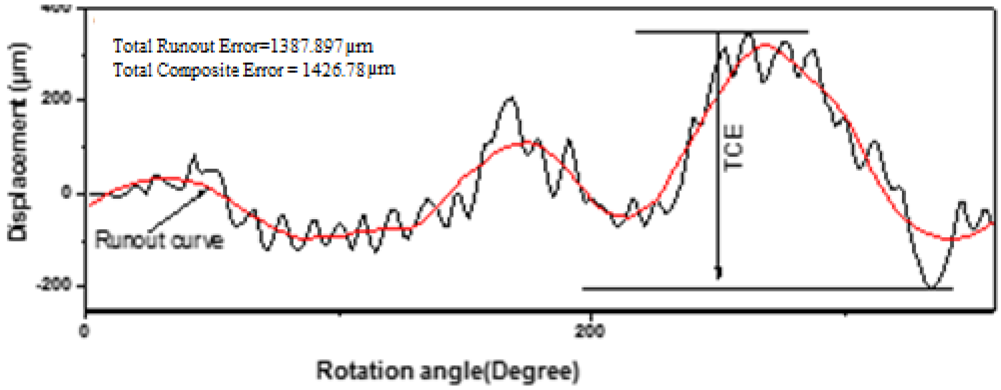
Experiments are performed on double flank gear roll tester for measuring total composite error, total runout error of the test gear. The error in the gear is measured by means of displacement of floating slide with respect to rotational angle of master gear. Before starting the experiment following procedure is selected,

- Mounting master gear on mandrel of fixed slide and make sure that there would not be any play between mandrel and master gear.
- Mounting of test/workpiece gear on floating slide and make sure there would not be any play between mandrel and test/workpiece gear.
- Before starting it make sure that master gear is in dual contact with test/workpiece gear i.e at zero blacklash which can be done using ball screw arrangement.

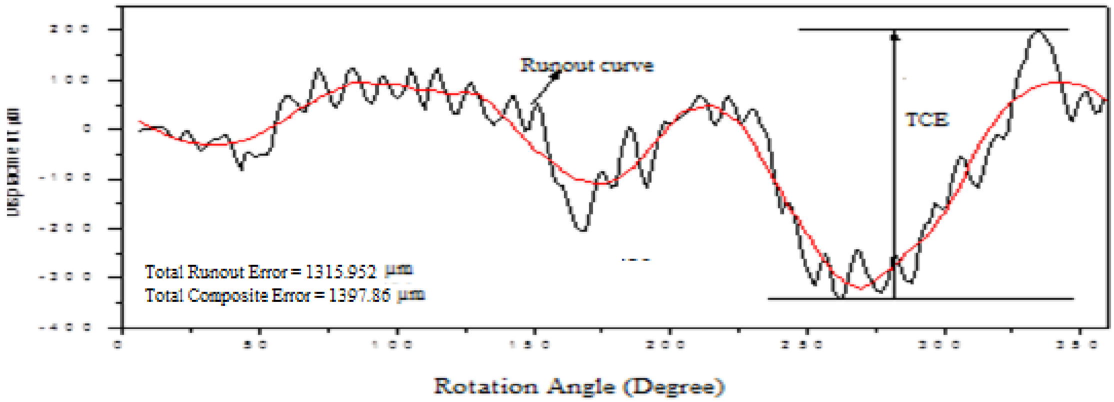
Readings are taken with the help of an non contact type comparator or Laser displacement sensor (LDS). LDS is fixed at 80 mm distance from the end face of a floating slide. LDS is connected to data acquistion system which converts the output pulses into usable form of data. Now all the connections have been made and measurements are taken, the displacement of floating slide is measured by LDS and this LDS has its own software which generates a file of formate **'.csv'** which can be opened in Ms Excel^{tm} sheet and the data can be used to plot the graph using origin 9.0 tool. For measuring the total runout in the test gear, 48 points smoothening is adopted which can be seen as red lined curve in a double flank testing report.

Measurements were performed three times for each gear to know about the repeatibility of the double flank gear roll tester. Table 4.1 presents the results of total composite errors and total runout errors for the spur gear pairs finished by AFF and PECH processes and WEDM manufactured near net-shape gears. The results are shown in the form of curve with irregular peaks and valleys. These peaks and valleys do have a significance that uniform tooth to tooth variation shows profile variation whereas a sudden jump indicates the pitch variations.

4.2 Results for Unfinished Gear



(a)



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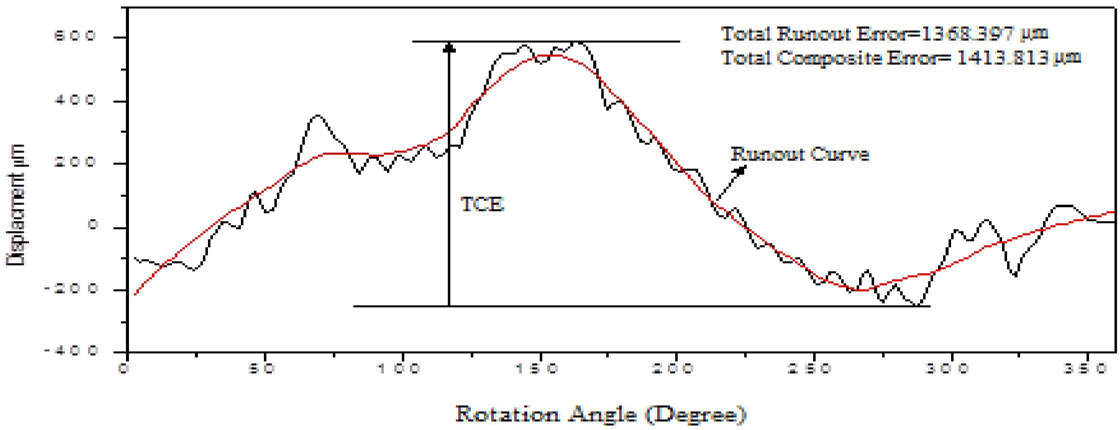


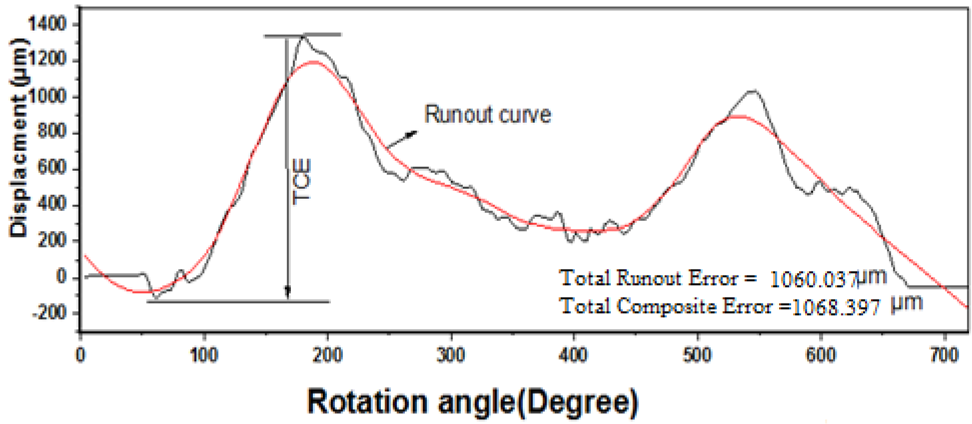
(c)

Fig. 4.1: Results of double flank testing for **unfinished i.e. hobbed** spur gear for different runs (a) run no. 1; (b) run no. 2; and (c) run no. 3.

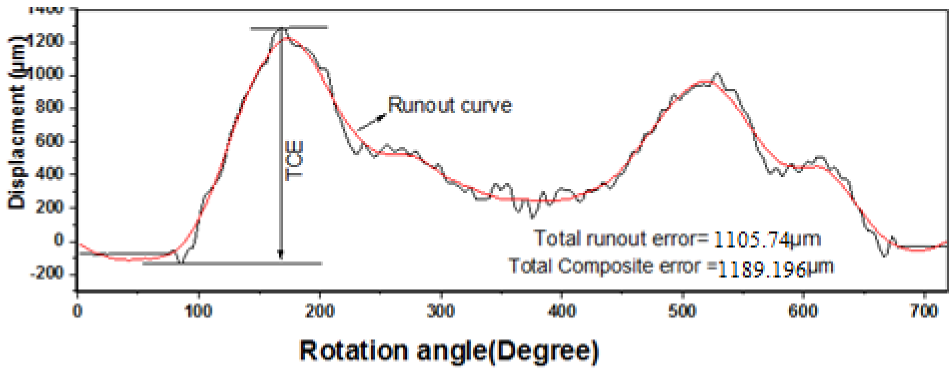
Results shown in fig.4.1 are the testing report of unfinished gears on roll tester,and each gear is tested thrice starting from different tooth to check the repeatability of the machine. We can interprete from the results that the unfinished gear have large profile and pitch deviations because uniform tooth to tooth variation shows profile variation whereas a sudden jump indicates the pitch variations.

4.3 Results for AFF Finished Gears

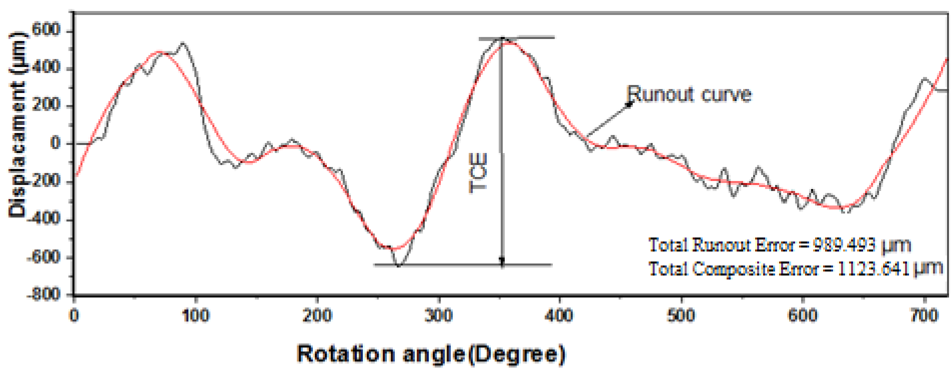
Three test gear were finished using the optimum values of AFF parameters by co researcher Gaurav Kumar and identified by **Petare and Jain (2017).** These values are : 50 bar as extrusion pressure; 150 mesh as size of abrasives; 30 (wt.%) as gravimetric concentration of abrasives in the AFF medium (silly putty + silicon oil) ; and 15 minutes as finished time.



(a)

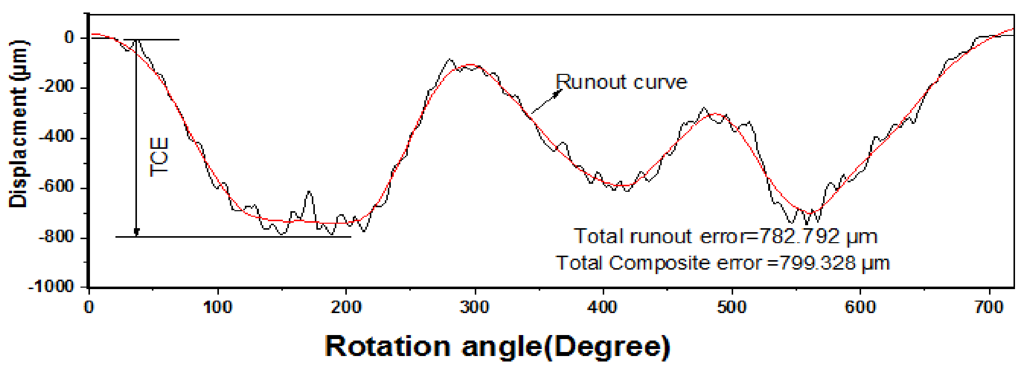


(b)

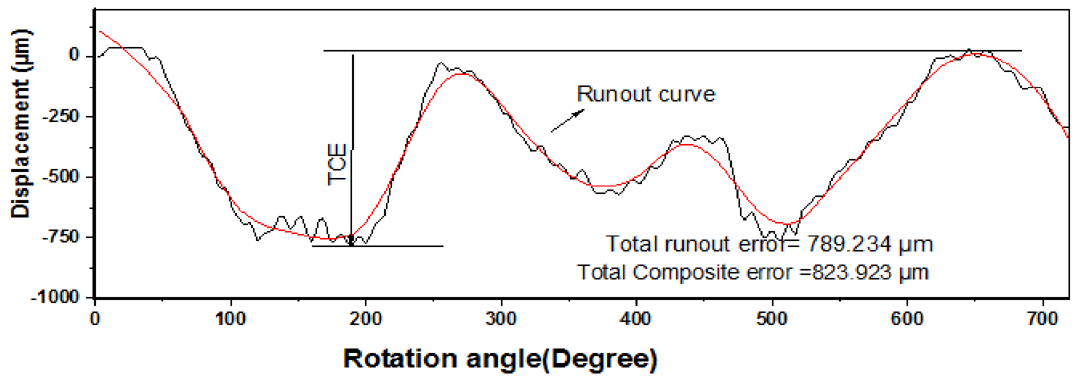


(c)

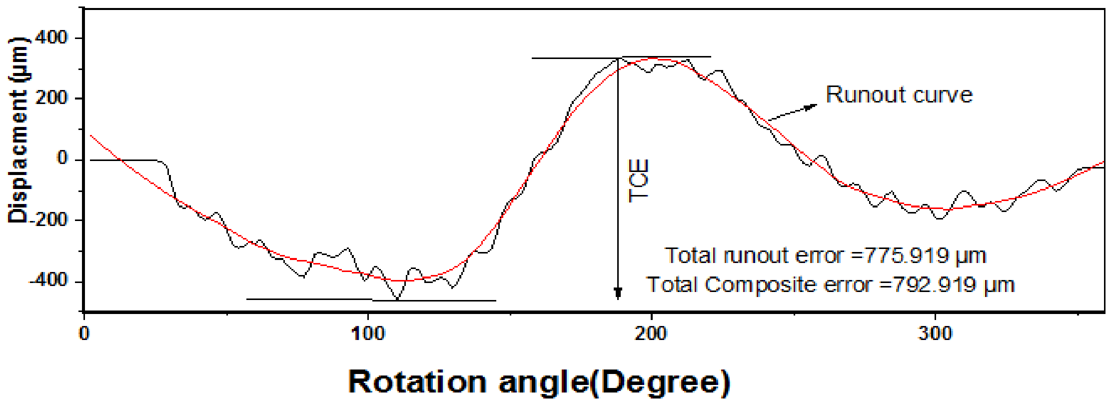
Fig. 4.2: Results of double flank testing for **spur gear number 1** finished by **AFF** process for different runs (a) run no. 1; (b) run no. 2; and (c) run no. 3.



(a)



(b)



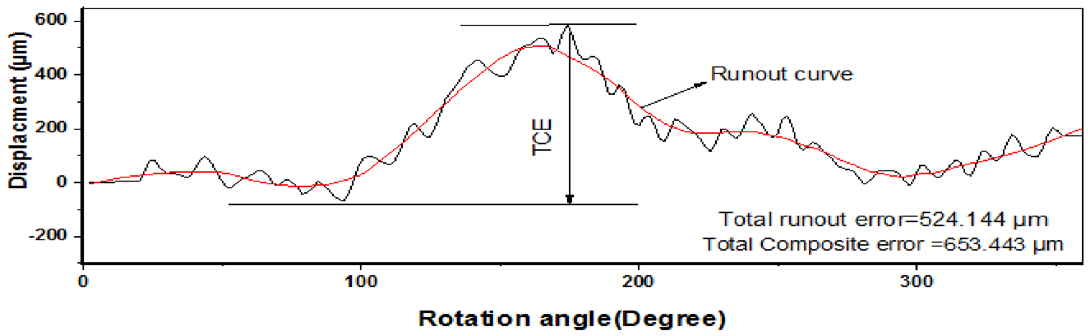
(c)

Fig. 4.3: Results of double flank testing for **spur gear number 2** finished by **AFF** process for different runs (a) run no. 1; (b) run no. 2; and (c) run no. 3.

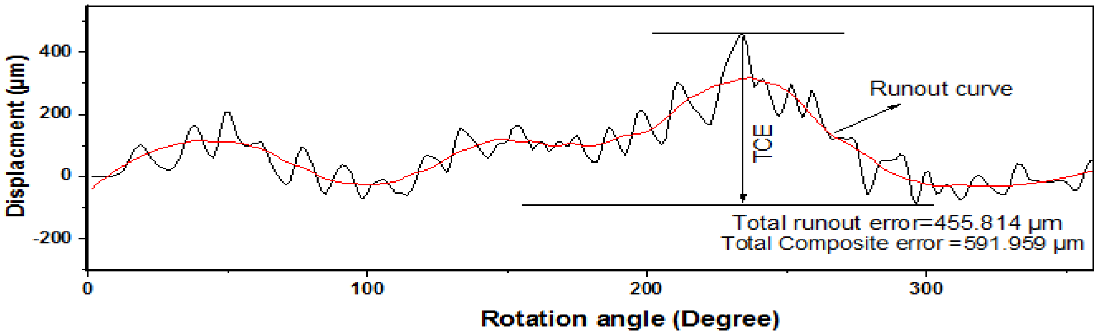
Fig 4.2, 4.3, shows the test report of AFF finished spur gears. From fig.4.2 we can interepret the results as gear no 1 has more pitch deviations as compare to profile deviations because in the graph (a),(b) and (c) there are more non uniform peaks than uniform peaks.From fig.4.3 we can say that gear no 2 has more profile deviation than of pitch deviation and has less TCE and total runout than gear no 1. Effectivness of the process can be explained on comaparing the results of unfinished (fig.4.1) and AFF finished gears (fig 4.2, 4.3) i.e the difference between the total composite error and total runout error in the unfinished gear is greater than that of AFF finished gears, therefore we can say that with the help of AFF process profile and pith deviations are minimised. It can also be noted that at the same input parameters the improvement in the microgeometry is different for all the finished gear.

4.4 Results for PECH Finished Gears

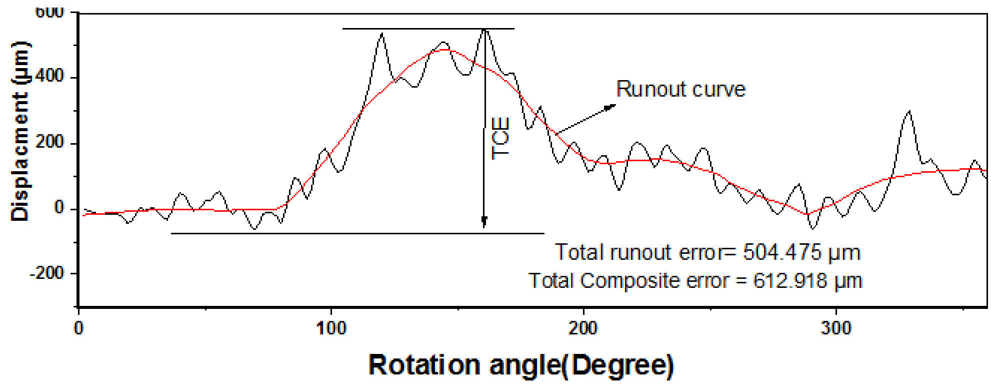
Two gears were finished by PECH process using optimum values of PECH process parameters by co researcher Gaurav Kumar and identified by **Rai (2016)**. This include: 3 ms as pulse-on time; 6 ms as pulse-off time; 16 Volts as voltage; 20A as current; 75 % NaCl + 25% $NaNO_3$ as electrolyte composition; 7.5% as electrolyte concentration; 30 litre per minute as electrolyte flow rate; 30°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.



(a)

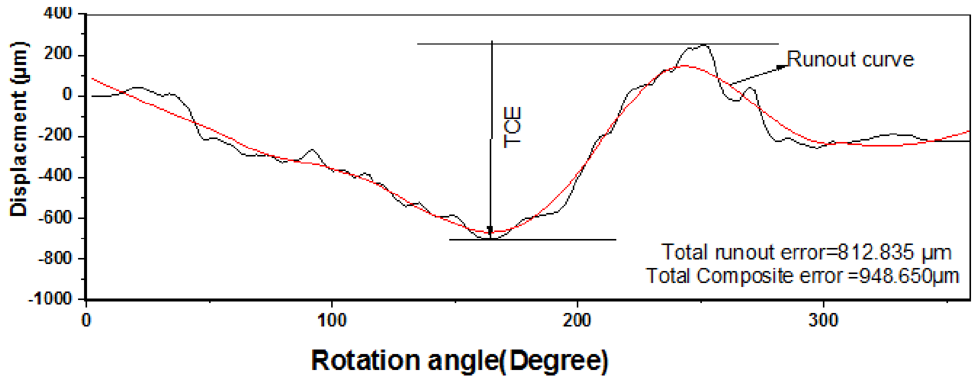


(b)

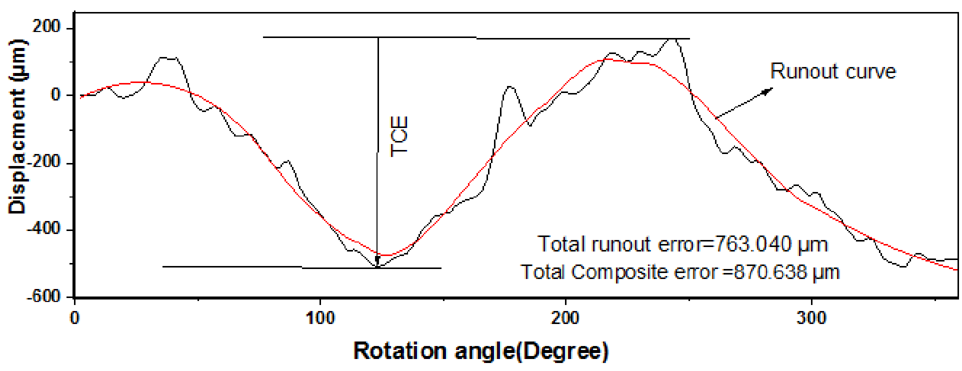


(c)

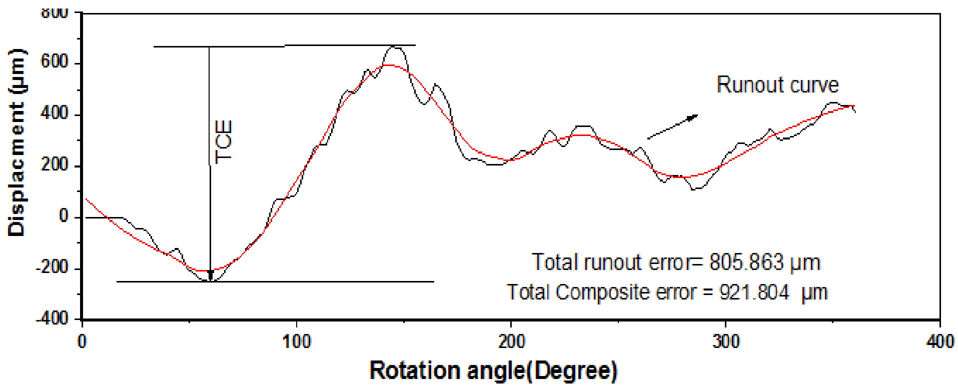
Fig. 4.4: Results of double flank testing for **spur gear number 1** finished by **PECH** process for different runs (a) run no. 1; (b) run no. 2; and (c) run no. 3.



(a)



(b)

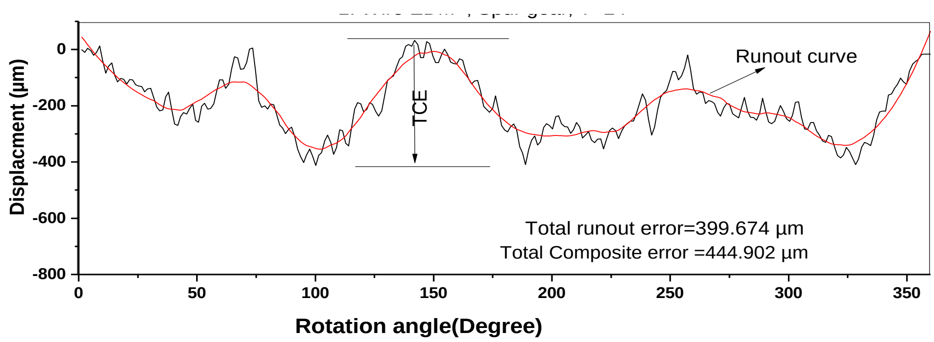


(c)

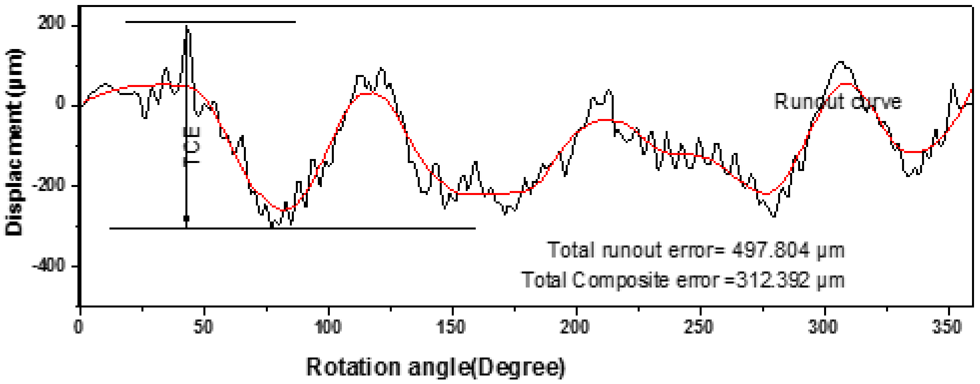
Fig. 4.5: Results of double flank testing for **spur gear number 2** finished by **PECH** process for different runs (a) run no. 1; (b) run no. 2; and (c) run no. 3.

Fig.4.5, 4.6 shows the test results of gears finished by PECH process. From fig.4.5 shows the results of gear no 1 finished by PECH process and interpretation shows that this gear has large profile as well as pitch deviations as of unfinished gear but has less TCE. Fig 4.6 shows the results of gear no 2 which shows that this gear has lesser profile deviations compared to pitch deviations and seems to be finished. But has large value of TCE because it has major component of radial runout which may come because of manufacturing defects.

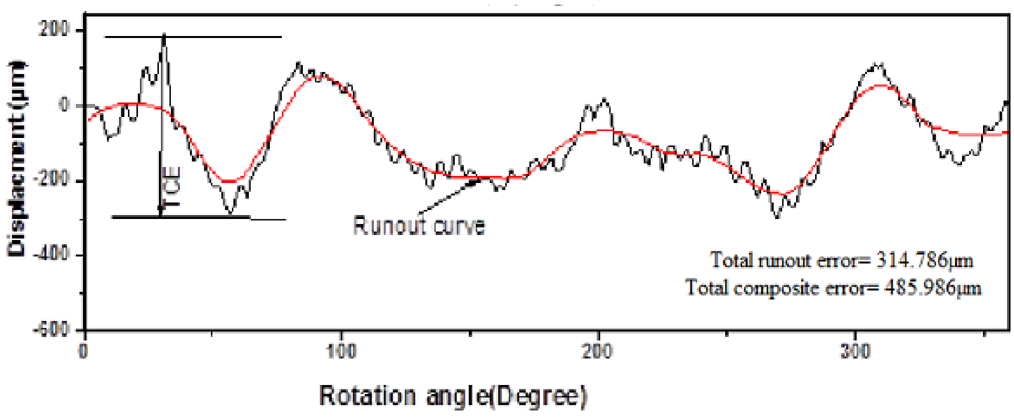
4.5 Results for WEDM Manufactured Near Net-shape Gears



(a)



(b)



(c)

Fig. 4.6: Results of double flank testing for near net-shaped spur gear **manufactured** by **WEDM** process for different runs (a) run no. 1; (b) run no. 2; and (c) run no. 3.

Gear manufactured by WEDM process was tested on roll tester and results are showed in fig. 4.7 results shows the gear is having large portion of profile deviation as well as pitch deviations because of irregular peaks but has less value of TCE.

Table 4.1: Summary of results of double flank testing of spur gears finished by AFF and PECH processes and near net-shaped manufactured by WEDM process.

Gear Condition	Gear no.	Runout error (mm)					Total composite error (mm)			
		Run no.1	Run no.2	Run no.3	Avg.	Measured analytically	Run no.1	Run no.2	Run no.3	Avg.
Unfinished		1.387	1.315	1.368	1.356	0.186	1.426	1.397	1.413	1.412
AFF finished	1	1.060	1.105	0.989	1.051	.170	1.068	1.189	1.122	1.336
	2	0.782	0.789	0.775	0.782	.149	0.799	0.823	0.792	0.804
PECH finished	1	0.524	0.455	0.504	0.494	0.170	0.653	0.591	0.612	0.618
	2	0.812	0.763	0.805	0.793	0.302	0.948	0.870	0.921	0.913
Near net-shape manufactured gear by WEDM		0.399	0.312	0.314	0.341	0.0724	0.444	0.497	0.485	0.475

4.6 Discussion

On the basis of these results it can be observed that gears of better quality have low values of total composite error and total runout error. It is also observed from the readings that the experimental apparatus of double flank gear roll tester is repeatable up to some extent, though it is not precise when we compare the radial runout results with the results of analytical testing by CNC gear metrology machine. ***The profile and pitch anomalies present in the gears are minimized in AFF process on comparison with PECH process of gear finishing*** because it has been seen that gears which are finished by AFF process have lesser irregularities in the curves as compare to PECH finished gear. Similarly, runout errors are minimum in PECH process on comparing with AFF process i.e. PECH can improve the runout present in the gear. Therefore, it would be difficult to comment on the processes but the runout error can be minimized at the manufacturing facility by taking care of cutter and circularity of gear blank but profile and pitch errors can only be improve by advanced finishing processes (AFF, PECH).

From the table 4.1 it is also clear that near net shape gear cut by WEDM have lower total composite and total runout error.

- Advanced gear manufacturing process (WEDM) has lower total composite error and total runout error compared to a gear finished by advanced process.
- From the table 4.1 it is also observed that each gear is tested thrice on roll tester and each time the results are quite repeatable therefore we can say that the dual flank gear roll tester experimental apparatus have good repeatability but is less accurate.
- It has been observed from table 4.1 that the results obtained from the test have higher values of total composite and total runout error which are unexpected. It may be possible to have such a high figures because of following reasons,
    - It may be because apparatus is not rigid as it should be.
    - There may be possibility of clearance between shaft and bearing of either floating or fixed slide which will give higher values of runout.
    - The master gear should ideally have DIN no of 5 for measuring the gear quality of DIN no 8 or higher but here we are using master gear of DIN no 11 to 12 therefore it may be the reason for higher irregularities present in the test gear results.
    - The irregularities in the results can be arise because of vibration due to stepper motor.

These all may be the reason for such a high figures.

Chapter 5

Conclusions and Scope for Future Work

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

5.1 Conclusions

Following conclusions can be summarized from the present research work-

- Advanced gear manufacturing process (WEDM) have lower total composite error and total runout error compared to a gear finished by advanced process.
- Gear finished by AFF process has lesser irregularity in the double flank gear toll test report compared to PECH finished gear i.e. AFF finished gear has less profile and pitch deviations then PECH.

5.2 Scope for Future Work

The present work was very first attempt to fabricate the roll tester and compare the total composite error and total runout error for the gears finished by the advanced gear finishing processes.

- Compare all the unconventional finishing processes for spur gears with master gear of high accuracy.
- Improvement can be made in the apparatus such as rigidity, circularity in the mandrel, and some cheap parts can be replaced by standards parts.
- Instead of providing pre-set force by spring we can implement pneumatic system in the apparatus.
- Software can be developed for this apparatus so that some important information can be directly reported like tooth to tooth composite error.
- The complete apparatus can be developed using PLC control so that manual handling can be reduced which will add to higher sensitivity of apparatus .

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