# Investigations on Laser Lay Profiling on Surface Quality and Microgeometry of Spur Gears for Finishing by AFF

**M.Tech Thesis**

by

**Ankit Mishra**

**Discipline of Mechanical Engineering**

**Indian Institute of Technology Indore**

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# Investigations on Laser Lay Profiling on Surface Quality and Microgeometry of Spur Gears for Finishing by AFF

**A THESIS**

*Submitted in partial fulfillment of the*

*requirements for the award of the degree*

*of*

**Master of Technology**

*in*

**Mechanical Engineering**

*with specialization in*

**Production and Industrial Engineering**

*by*

**Ankit Mishra**

**Discipline of Mechanical Engineering**

**Indian Institute of Technology Indore**

**July 2018**

# Indian Institute of Technology Indore

## Candidate's Declaration

I hereby certify that work which is being presented in the thesis entitled **"Investigations on Laser Lay Profiling on Surface Quality and Microgeometry of Spur Gears for Finishing by AFF"** in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** in **Mechanical Engineering** with specialization in **Production and Industrial Engineering** 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 from **May 2017 to July 2018** under the supervision of **Professor Neelesh Kumar Jain,** and **Dr. I.A. Palani** 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.

**Ankit Mishra**

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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. I.A. Palani**

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**Ankit Mishra** has successfully completed his M. Tech Oral Examination, held on **……**

Signature of M.Tech. Thesis Supervisors Signature of Convener, DPGC
Date: Date:

Signature of PSPC Member 1 with date (**Prof. Anand Parey**)

Signature of PSPC Member 2 with date (**Dr. S. Vasudevan**)

Signature of Chairman, Oral Examination Board with date

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**Ankit Mishra**

*Dedicated*

*To*

*My Parents*

# Abstract

Higher wear resistance, lower noise level, enhance power transmission capability, better transmission efficiency, operating performance and longer service life are continuously growing expectations from the gears. These expectations can be met by manufacturing the gears of better quality. Manufacturing of better quality gears requires minimizing errors or deviations in microgeometry parameters, surface roughness parameters and improving surface integrity (i.e. residual stresses, microstructure, microhardness etc.) of the gear flank surfaces by appropriate gear finishing process.

Laser surface texturing provides micro-reservoirs to enhance lubricant retention or micro-traps to capture wear debris. Presence of micro-texture improves friction and wear characteristics of materials. But, it arises excess melt material on the surface as an artifact from the laser processing. These melt and excess re-solidified material need to be removed through finishing methods to achieve intended surface geometry and quality. Abrasive flow finishing (AFF) is an advanced finishing process. Present work is focused on investigating the effect of laser lay profiling on microgeometry and surface quality of 20MnCr5 alloy steel spur gears finished by AFF process. Homothetic textured lay profile was created by laser beam of 1064nm wavelength on the hobbed spur gears in direction normal to lay profile by hobbing and later it was finished by AFF process. The finishing performance of hobbed spur gears and laser lay profiled hobbed spur gears by AFF in terms of microgeometry deviations (i.e. profile, lead, pitch and runout), surface quality (i.e. average surface roughness, maximum surface roughness), material removal rate, microhardness and wear rate were compared. Extrusion pressure of 5 MPa, finishing time of 25 minutes and abrasive particle (SiC) of mesh size 100 with 30 % weight concentration produced the best surface quality gear. This research shows the maximum percentage reduction in average surface roughness ($PRR_a$), maximum surface roughness ($PRR_{max}$), total profile error (*PRFa*), total lead error (*PRFb*), cumulative pitch error (*PRFp*), and runout error (*PRFr*) as 69.12%, 68.92%, 28.49%, 40.20%, 24.85%, 4.80% respectively for laser lay profiled spur gear finished by AFF which is more as compared to 61.27%, 48.14%, 21.55%, 38.97%, 15.95%, 3.93% respectively for spur gear directly finished by AFF. Higher improvement is observed in microgeometry, surface quality, material removal rate, microhardness and wear resistance for finishing of hobbed spur gear with laser lay profiling by AFF process as compared to finishing of hobbed spur gear with laser lay profiling by AFF with same finishing time. This will increase operating

performance and service life of gears which prevent premature failure, low running noise and vibration.

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## Nomenclature

| | |
|---|---|
| $F_a$ | Total profile error |
| $F_b$ | Total lead error |
| $F_P$ | Cumulative pitch error |
| $F_r$ | Runout error |
| $R_a$ | Average surface roughness |
| $R_{max}$ | Maximum surface roughness |

# Acronyms

| | |
|---|---|
| AFF | Abrasive Flow Finishing |
| ECH | Electro Chemical Honing |
| EDM | Electric Discharge Machining |
| LST | Laser Surface Texturing |
| *MRR* | Material Removal Rate |
| PECH | Pulse Electro Chemical Honing |
| $PIR_a$ | Percentage Improvement in average surface roughness |
| $PIR_{max}$ | Percentage Improvement in maximum surface roughness |
| $PIF_a$ | 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 error |
| UA-AFF | Ultrasonic Assisted-Abrasive Flow Finishing |

# 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 types based on several criteria as listed below:

### 1.2.1 According to the Position of Axes of Revolution

- **Gears having parallel axes of their mounting shafts:** Such type of gears are manufactured from cylindrical blank therefore, they are called **cylindrical gears**. Following are different types of cylindrical gears:
  - **Spur gear:** Spur gears 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
  - Helical Gear
    - Single Helical Gear
    - Double Helical Gear (or) Herringbone Gear

- **Gears having intersecting axes of their mounting shafts:** Such type of gears are manufactured from frustum of a conical blank therefore, they are called **conical gears**. Following are different types of conical gears:
  - Bevel Gear
    - Straight bevel gear
    - Spiral bevel gear
    - Zero bevel gear
    - Hypoid bevel gear
  - Angular gear
  - Miter gear
- **Gears having non-parallel and non-intersecting axes of their mounting shafts**: Such type of gears are referred as **skew shaft gears.** Following gears belong to this category
  - Worm gear
    - Non-throated worm gear
    - Single-throated worm gear
    - Double-throated worm gear
  - Hypoid gear
  - Crossed-helical gears or screw gears

### 1.2.2 Based on the type of Gearing

- Internal gear
- External gear
- Rack and Pinion

### 1.2.3 Based on the Tooth Profile on the Gear Surface

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

### 1.2.4 Based on the Peripheral Velocity of Gears

- Low velocity gears – Gears with peripheral velocity < 3 m/s
- Medium velocity gears – Gears with peripheral velocity = 3-15 m/s
- High velocity gears – Gears with peripheral velocity > 15 m/s

Spur gear

Helical gear

Rack and Pinion

Herringbone gear

**Cylindrical Gears**

Spiral bevel gear

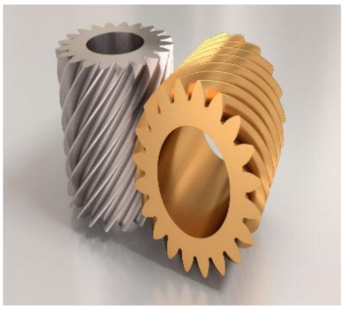
Miter gear

Straight bevel gear

**Conical Gears**

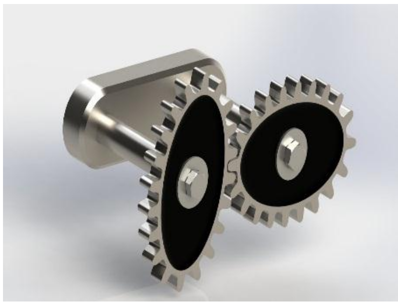
Worm and worm wheel

Hypoid gear

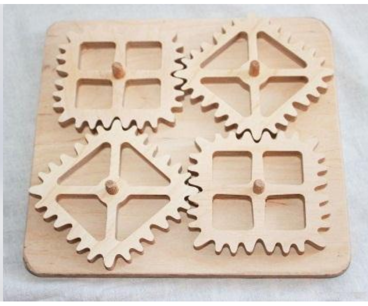


Crossed-helical gears

**Skew shaft Gears**



Oval gear



Square gear

Triangular gear

Sector gear logarithmic gear

**Different types of non-circular gears**

**Internal gear**

**Figure 1.1:** Different types of gears.

## 1.3 Applications of Gears

Gears are used in various industries in numerous machines. The list below contains the main application fields of gears **(Jain and Petare, 2018a):**

- Automobile (i.e. cars, trucks, tractor, motor-cycles, scooter, etc.)
- Transportation (i.e. buses, train, subways, etc.)
- Aerospace (i.e. high-speed aircraft engine.)
- Marine (i.e. high power high speed marine engine, navy fighting ships)
- Control systems (i.e. gun, helicopter, jets, tanks, etc.)
- Machine tool and material handling industry
- Agriculture machinery (i.e. threshers, harvesters, etc.)
- Oil and gas industry (i.e., oil platforms, pumping stations, drilling sites, refineries and power stations)
- Home appliances (i.e. washing machine, food mixtures, fans, etc.)
- Various mechanism, toys, watches and gadgets.

## 1.4 Expectation from the Gears

Higher wear resistance, lower noise level, enhance power transmission capability, better transmission efficiency and operating performance and longer service life are continuously growing expectations from the gears. These expectations can be met by manufacturing the gears of better quality. Manufacturing of better quality gears requires (i) minimizing deviations in microgeometry parameters (i.e. parameters related to profile and lead which describe form of gear teeth and parameters of pitch and runout which describe location accuracy of gear teeth), (ii) minimizing surface roughness parameters (i.e. maximum and average surface roughness, surface roughness depth, material contact ratio and flank surface topography), and (iii) improving surface integrity (i.e. residual stresses, microstructure, microhardness, etc.) of the gear flank surfaces by appropriate gear finishing process. Conventional finishing processes such as shaving, honing, burnishing, grinding and lapping are generally used to finish the gears to achieve their better quality.

## 1.5 Limitations of Conventional Finishing Processes for Gears

Conventional finishing processes for gears suffer from following major limitations (Petare and Jain, 2018a) which restrict their wide applications for different types of gears:

### 1.5.1 Gear Grinding

- Gear grinding results in undesirable effect such as Grinding burns caused by high temperature damage surface integrity of the ground gears and can even sometime lead to gear failure through tooth breakage and transverse grind lines on the finished surface which causes noise and vibration of the gears.
- Ground gear teeth have defects such as fine cracks, thermal distortion, and uneven stress distribution over the gear tooth surface. To detect these defects nondestructive technique is required which is costly.
- Control of rate of heat generation is required to eliminate cracking and burning of gear surface. This requires use of cutting fluid and frequent dressing of grinding wheel which increases the cost of finishing.
- It is only finishing process other than gear honing which can finish hardened gears having hardness value more than 40 HRC.

### 1.5.2 Gear Lapping

- Gear lapping corrects only minute errors in the involute profile, helix angle, tooth spacing and concentricity produced during either manufacturing or heat treatment of the gears.

- It is very slow process and is costly as compared to other finishing methods. Material removal in lapping usually ranges from 0.003 to 0.03 mm but many reach up to 0.08-0.1 mm in certain cases.
- Low MRR and non-uniform lapping over tooth surface result poor correction in profile error.

### 1.5.3 Gear Honing

- It can be used only for unhardened gears.
- Limited life of honing tool.
- Honing time increases as error in tool shape increases.

### 1.5.4 Gear Shaving

- Gear shaving can finish either unhardened gears or gears having hardness value up to 40 HRC only.
- Shaving causes removal of more material from gear tooth surface around pitch points of a gear. This adversely affects gear tooth surface finish and their transmission quality especially when they have true involute profile.
- Shaved gears have a step marks left on gear teeth the end of the involute profile which causes excessive noise, wear and vibration.

Above-mentioned limitations have prompted the development of advanced finishing processes such as Abrasive Flow Finishing (AFF), Electrochemical Honing (ECH), Pulse Electrochemical Honing (PECH), Ultrasonic Assisted AFF (UA-AFF) etc. Consequently, some unconventional processes have been developed 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 and Jain, 2013**).
- Pulsed-ECH (PECH) for finishing spur gears (**Mishra et *al.*, 2012**), helical gears (**Rai, 2016**) and straight bevel gears (**Pathak et *al.* 2014**).
- Finishing of bevel gears by AFF process (**Venkatesh et *al.*, 2014**) and by Ultrasonic Assisted AFF (UA-AFF) (**Venkatesh et *al.*, 2015**).
- Finishing of spur gears by AFF process (**Petare and Jain, 2018b**).

## 1.6 Lay Profile

Lay is dominating pattern of marks left on the surface due to machining processes, it is made up of roughness and waviness. Surface structure is an interesting property, it is reasonable to believe that interaction of contact surfaces lay profile can play a significant role. Lubricant retention volume, relative sliding speed direction, wear, penetration depth and all other tribological properties will be affected. Surface lay profile direction can be affected by the manufacturing procedures through the design of the tool, relative speed between tool and workpiece **(Mehta and Rathi, 2013).**

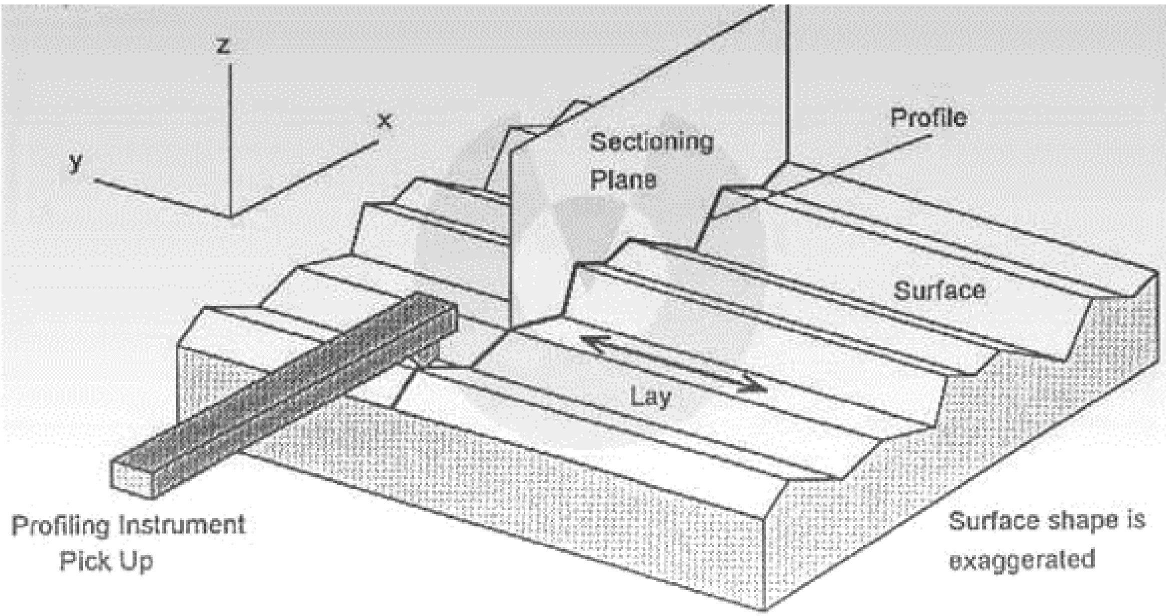



**Figure 1.2:** Details of lay profile.

There are different types of lay profile formed due to various machining and finishing processes such as parallel lay profile formed due to planning, shaping and hobbing, crosshatch or diagonal lay profile formed due to honing, multi- directional lay profile formed due to milling, circular lay profile formed due to plane turning. Among these process gear honing is the most significant process provides the crosshatch lay profile pattern, which facilitates the formation of a lubrication film on gear surface thereby positively influences the noise behavior in the gearbox, prolong wear life and increases the load carrying capacity.

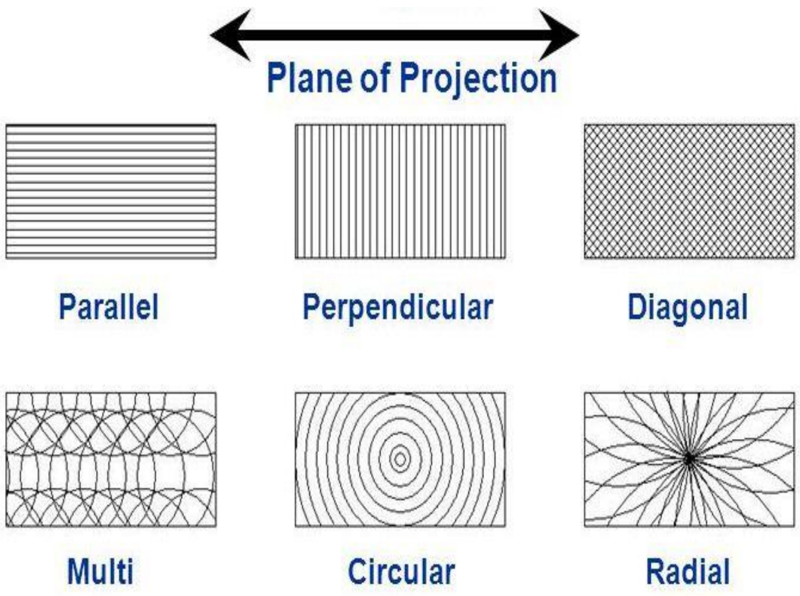
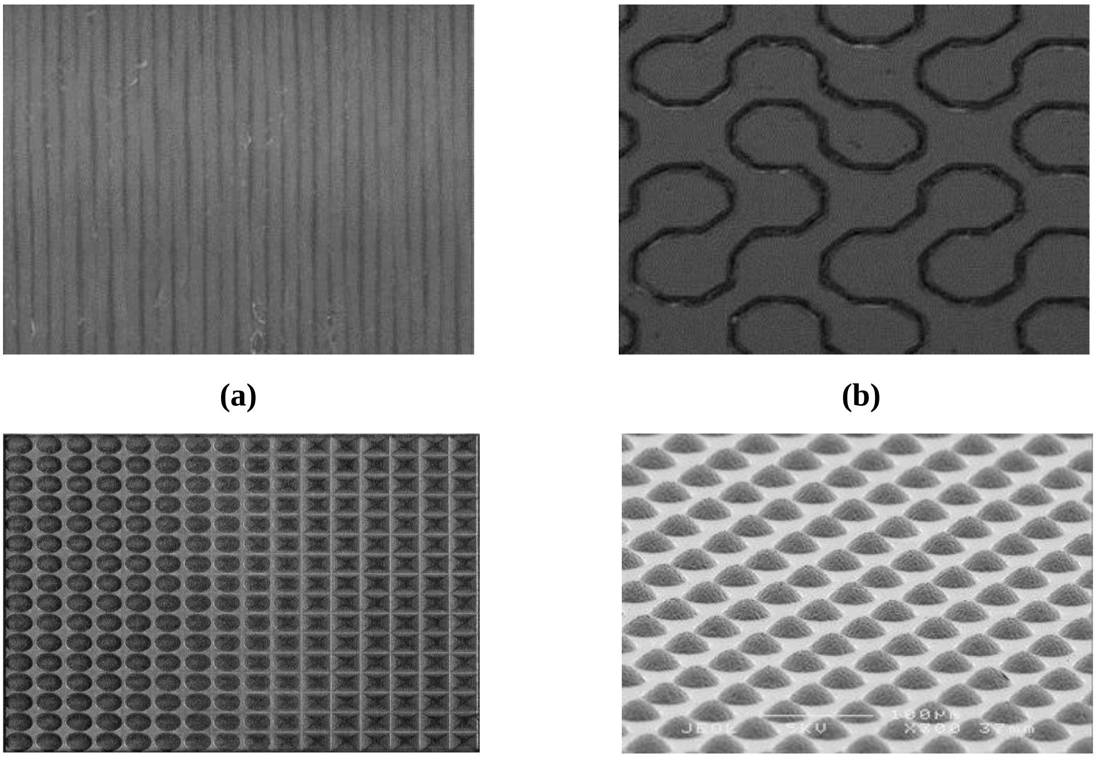



**Figure 1.3:** Different types of lay profiles generated due to different machining and finishing processes.

## 1.7 Laser Surface Texturing

Surface texturing has emerged in the last decade as a viable option of surface engineering resulting in significant improvement in load capacity, wear resistance, friction coefficient etc. of mechanical components. Various techniques can be employed for surface texturing but Laser Surface Texturing (LST) is probably the most advanced so far. This is because the laser is extremely fast, clean to the environment and provides excellent control of the shape and size of the micro pattern, which allows realization of optimum designs. Indeed, LST is starting to gain more and more attention in the tribology community as is evident from the growing number of publications on this subject.

Nowadays, Laser Surface Texturing (LST) is frequently used by researchers and industries to improve tribological properties and fatigue life of materials. LST provides micro-reservoirs to enhance lubricant retention or micro-traps to capture wear debris. Presence of micro texture improves friction and wear characteristics of materials. LST relies on the target material being melted, ablated, and blown away by high intensity laser beam. After LST has been performed, excess melt material on the surface as an artifact from the laser processing. These melt and excess re-solidified material need to be removed through finishing methods to achieve intended surface geometry and quality. This finishing can be done with fine abrasives and standard mechanical finishing Processes. Most frequently used laser textures are homothetic (parallel line), wavy (curved), spot, micro-dimples, micro-pillar of the square and triangular cross section etc.



(a) (b)

(c) (d)

**Figure 1.4:** Optical micrograph of different types of laser texturing (a) homothetic or parallel, (b) wavy or curved, (c) micro-dimple, and (d) micro-pillar **(Zhang *et al.*, 2017).**

## 1.8 Organization of the Thesis

**Chapter 2** presents review of the past work on finishing of gears by abrasive flow finishing (AFF) and AFF assisted processes, laser texturing, the identified research gaps, the research objectives defined to bridge the identified research gaps and research methodology used in the present work.

**Chapter 3** reports on planning and details of the experimentations for generating laser lay profile on hobbed spur gear and finishing of hobbed spur gears with laser lay profiling by AFF and finishing of hobbed spur gears without laser lay by AFF process.

**Chapter 4** presents results of microgeometry, surface roughness, microhardness and wear resistance of hobbed spur gear with laser lay profiling after finishing by AFF process and hobbed spur gear without laser lay profiling after finishing by AFF process.

**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 of Past Work and Research Objectives

This chapter describes review of past work on lay profiling of gears, laser texturing on different materials and gears finished by AFF and AFF assisted processes, identified research gaps, the research defined to bridge the identified research gaps and research methodology used in the present work.

### 2.1 Past Work on Lay Profiling of Gears

**Mehta and Rathi (2013)** reviewed on internal gear honing process and they concluded that among three gear finishing processes like internal gear honing, grinding and green shaving, internal gear honing is most efficient process provides an excellent surface finish of the sprockets compared to the other processes and Honed gears produce less noise and have a longer life than other gears due to their typical surface lay pattern.

### 2.2 Past Work on Laser Texturing on Different Materials

**Xing et *al.* (2013)** created laser texturing on $Si_3N_4$/TiC ceramic and investigate anti-wear performance by a ball-on-disk tribo-test and finite element analysis (FEA) for stress distribution. They concluded (i) tribological features influenced by size and density grooves created by laser; (ii) Wavy grooves with large density gives low CF; and (iii) Texturing improves stress distribution pattern contact edges and reduce concentration of stress.

**Baharin et *al*. (2016)** Laser texturing showed high improvement of surface properties and reduction of coefficient of friction for Ti6Al4V, stainless steel and steel based nitride.

**Sasi et *al.* (2017)** attempted laser surface texturing high speed steel (HSS) tool for machining of aluminum alloy (Al7075-T6) for aerospace applications. They reported tribological properties of cutting tool enhanced for dry machining and texturing helped to reduced cutting and thrust force around 9 % and 19 % respectively.

**Kang et *al.* (2017)** applied laser texturing on injection cam of AISI 1045 steel materials for internal combustion engine to improve anti-wear properties. They reported 30 % improvement of anti-wear properties of laser textured injection cam compared to without textured injection cam.

**Niketh and Samuel (2017)** created micro-texture and micro-dimples by using laser on carbide drill of 8 mm size for drilling hole in Ti-6Al-4V. They reported reduction of 12.3% torque, 10.6% in thrust force and less built up edge (BUE) formation while comparing with non-textured drill tool.

## 2.3 Past Work on Finishing of Gears by AFF and AFF Assisted Processes

**Xu et *al.* (2013)** reported that the surface roughness of the helical gear decreases by increasing the number of machining cycle. The surface roughness Ra of the left tooth surface, right tooth surface and addendum before processing 1.429um, 1.108um and 2.732um dropped after processing 0.228um, 0.216um and 1.754um.

**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.

**Venkatesh et *al.* (2015)** reported that the finishing of bevel gears using US-AFF is more effective than conventional AFF process in term of finishing time and improvement in surface roughness.

**Petare and Jain (2018b)** reported the optimized parameters for improving spur gear microgeometry and surface finish by AFF process. Surface roughness, microgeometry deviations Reduction in pitch deviation and runout can be improved by appropriately designing the fixture. Finishing time and viscosity of medium are important parameters of AFF process affecting the micro geometry and surface roughness during their finishing by AFF process. There exists an optimum finishing time for attaining maximum improvement in microgeometry and surface finish of spur gears. Maximum values of $PIF_a$, $PIF_b$, $PIF_P$ are obtained at 135 kPas viscosity of AFF medium and 25 min of finishing time, whereas maximum value of '*PIFr*' is obtained at 54 kPas. and 20 min of finishing time.

## 2.4 Identified Research Gaps

Based on the review of the past work done following research gaps were identified on improving surface quality and microgeometry of spur gears.

- No work has been reported on microgeometry and surface roughness for finishing of hobbed spur gear with laser lay profiling by AFF process.
- No work has been reported on comparison of microgeometry and surface roughness for finishing of the hobbed spur gear without laser lay profiling and hobbed spur gear with laser lay profiling by AFF process.

## 2.5 Objectives and Research Methodology

- ❖ Optimization of laser parameter (gain, focal length, power, number of passes) for generating laser lay profile on the hobbed spur gears to assist their finishing by AFF process.
- ❖ Analysis and comparison of average and maximum surface roughness values and microgeometry of
  - Hobbed spur gear.
  - Laser lay profiled hobbed spur gear.
  - Hobbed spur gear without laser lay profiling finished by AFF process.
  - Hobbed spur gear with laser lay profiling finished by AFF process.

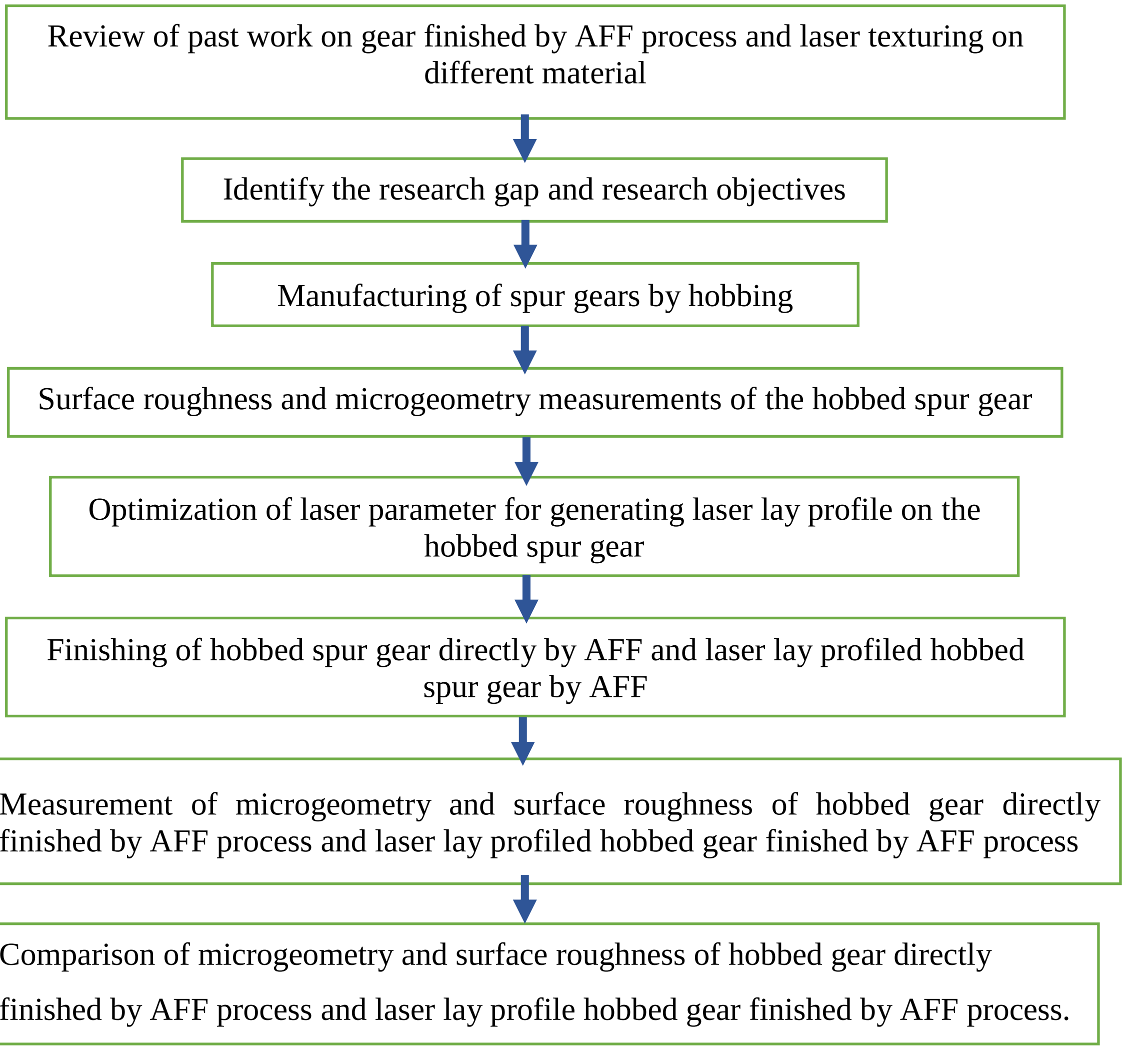



**Figure 2.1:** Research methodology flow chart

# Chapter 3

## Details of Experimentation

### 3.1 Specifications of the Gears

The gears used in the experiment were spur gears having 3 mm module, 16 teeth and made up of 20MnCr5 alloy steel. This grade of alloy steel was selected as gear material because it is mostly used in industry, chemically and electrically conductive, easily available and has good strength. Blanks for spur gears were manufactured on lathe machine and spur gear teeth were cut on gear hobbing machine.

**Table 3.1:** Spur gear specifications used as workpiece.

| Parameter | Details |
|---|---|
| Material | 20MnCr5 alloy steel |
| Module | 3 mm |
| Number of teeth | 16 |
| Pressure angle | $20^0$ |
| Pitch circle diameter | 48 mm |
| Face width | 10 mm |
| Addendum circle diameter | 54 mm |
| Root circle diameter | 40.5 mm |

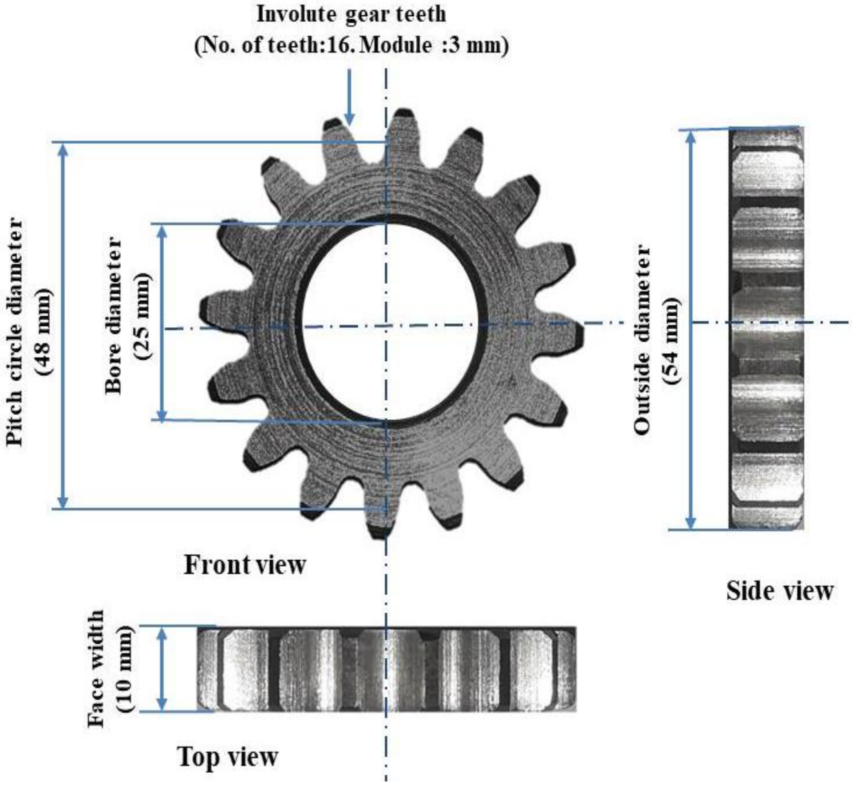
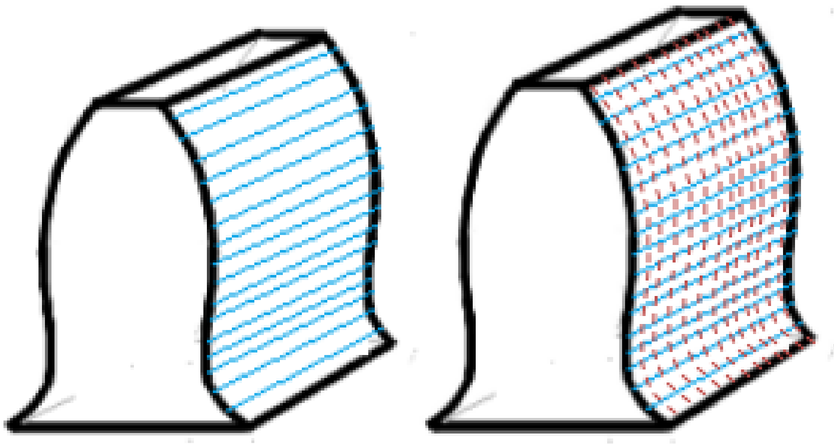


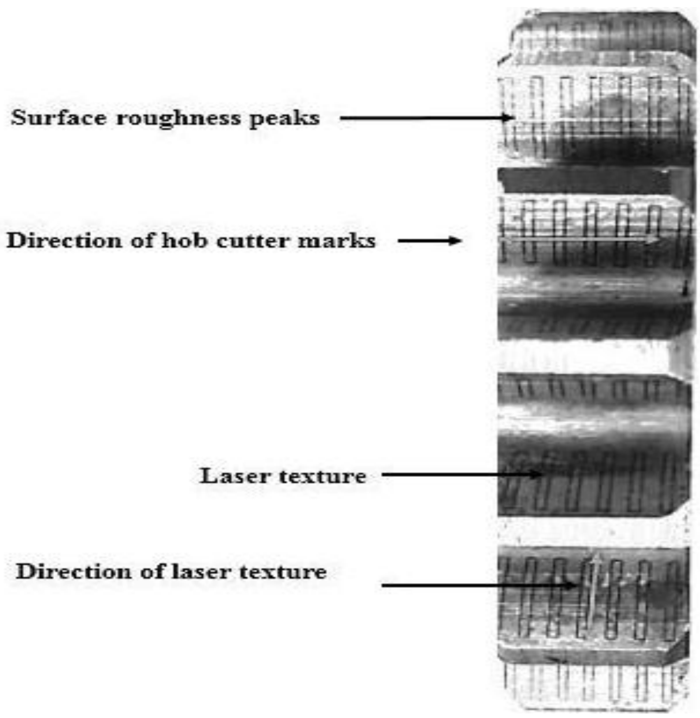

**Figure 3.1:** Photographs and specifications of the hobbed spur gear used as workpiece.

## 3.2 Laser Lay Profiling of the Hobbed Spur Gears

Homothetic textured lay profile is preferred on gear flank surface as it is perpendicular to hobbed lay profile resulting in reducing friction coefficient better than other direction (**Hao *et al.*, 2018)**. Homothetic texture and cutter marks formed a mesh like structure which deflect flow direction of abrasives medium and it will travel more distance and causes uniform abrasion and more material removal rate.



**(a)** **(b)**




**(c)**

**Figure 3.2:** Schematic of lay profile of a (a) hobbed spur gear; (b) laser lay profiled hobbed spur gear; and (c) photograph of the laser lay profiled hobbed spur gear.

**Lay profile generated by hobbing**

**Lay profile generated by the laser-based process**

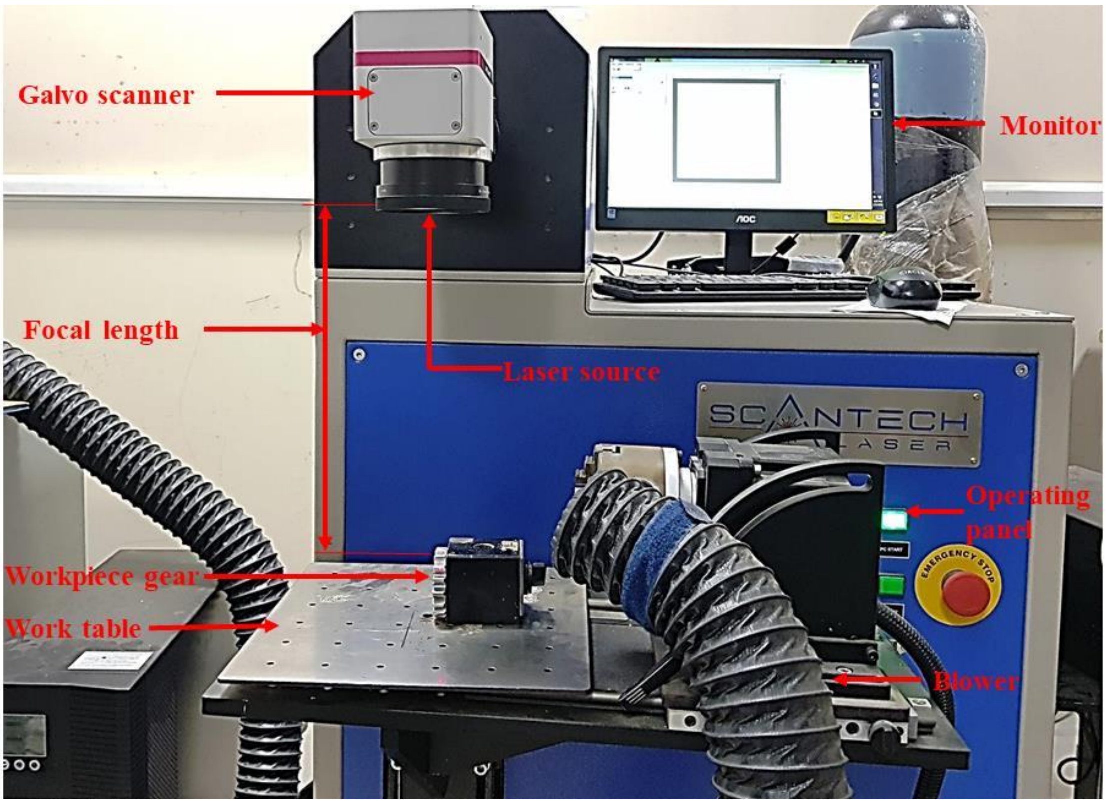



**Figure 3.3:** Photograph of continuous fiber laser apparatus (from Scantech Pvt. Limited Maharashtra, Mumbai) used for laser lay profiling of the spur gears.

### 3.2.1 Identification of the Optimum Parameters

Experiments were performed to identify optimum values of focal length of the laser, laser power, and number of passes using 1064 nm wavelength (fixed by fiber laser apparatus) and gain of 1.9 or marking height and length as 2.2 mm x 4.1 mm (concept depicted in Fig. 3.4) which was set according to the size of gear teeth flank. Table 3.2 presents details of the fixed parameters and variable parameters and their identified optimum values.

**Table 3.2:** Details of the parameters used in laser lay profiling of hobbed spur gear.

| **Parameters** | **Values used in experiments** | |
|---|---|---|
| **Fixed parameters** | | |
| Laser wavelength (nm) | 1064 | |
| Gain [marking height(mm) x length (mm)] | 1.9 [2.2 x 4.1] | |
| **Variable parameters** | **Values used in experiments** | **Identified optimum value** |
| Focal length (mm) | < 285 mm; 285 mm; > 285 mm | 285 |
| Laser power (watts) | 10; 15; 20; 25 | 20 |
| Number of laser passes | 1; 2; 5; 6 | 5 |

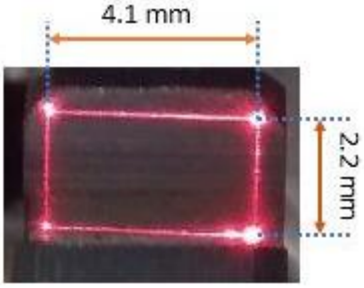
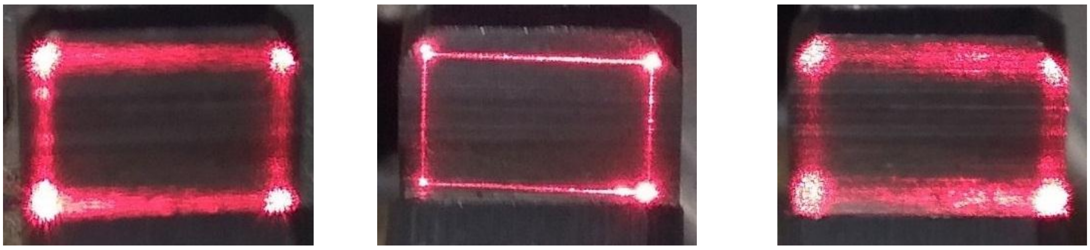



**Figure 3.4:** Concept of gain used in laser lay profiling of the hobbed spur gears.

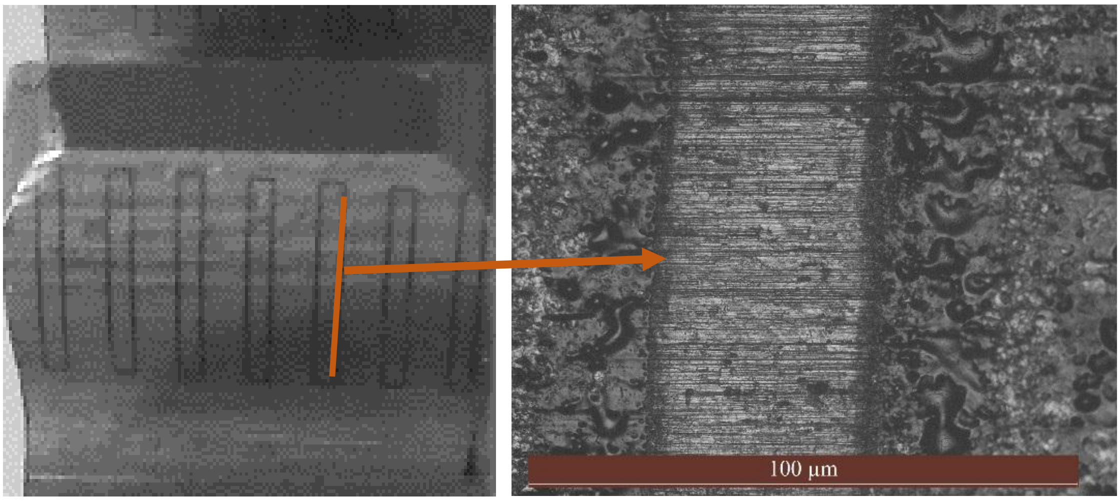
- **Focal length:** Figure 3.5 shows gain obtained using focal length less than 285 mm (Fig. 3.5a), equal to 285 mm (Fig. 3.5b), and more than 285 mm (Fig. 3.5c). It is evident from these figures that focal length equal to 285 mm from the galvoscanner enabled laser beam to form a sharp boundary and corners of the marking area for the lay profiling with pointed corner. For two other focal lengths, laser beam was scattered and formed blur boundary and corners of the marking area for the lay profiling.



**(a)** **(b)** **(c)**

**Figure 3.5:** Boundaries of the marking area on flank surface of spur gear for lay profiling at different values of focal length: (a) less than 285 mm, (b) at 285 mm, and (c) more than 285 mm.

- **Laser power and number of passes:** Visibility of laser texture on gear flank surface was checked visually by magnifying glass of 10x magnification. No laser texture formed till laser power of 15 W and 6 number of passes. Fine laser textures formed at 20 W of laser power and 5 number of passes. Use of 25 W laser power resulted in burn marks on hobbed spur gear tooth flank surface and increased density of texture. Therefore, 20 W as laser power and 5 as number of passes were identified as their optimum value for laser lay profiling of the spur gears. Figure 3.6a depicts flank surface of the laser lay profiled spur gear and Fig. 3.6b shows its optical micrograph at 100x magnification.




**(a)** **(b)**

**Figure 3.6: (a)** Laser lay profiled flank surface of the hobbed spur gear, and **(b)** its optical micrograph at 100X.

## 3.3 Finishing of Spur Gear by AFF Process

In recent years, improvement in material and manufacturing innovation took place rapidly to accomplish better quality at lesser cost. Main focus these new advancements were on decreasing the process duration and enhance the quality, performance and life of gears. Abrasive flow finishing (AFF) is an advanced finishing process which was introduced in 1960s with applications in deburring of the components made by electric discharge machining (EDM) process. Subsequently, its scope for material and shape applications are continuously increasing.

### 3.3.1 Working Principle of AFF Process

AFF process uses a mixture of hydraulically pressurized flow of shear thickening putty and abrasives to achieve material removal through abrasion. The workpiece gear is mounted on the fixture in such a way that it can withstand against high extrusion pressure and addition to it guides the medium through circumferential holes. The AFF medium is forced forward and backward through workpiece gear thus imparting very high-quality finish.

### 3.3.2 Fixtures for AFF of the Spur Gears

Finishing of gear in AFF process mainly depend upon the gear holding fixture because it allows the proper holding and exact location of the gear flanks in the desired position during it finishing. Design of the fixture used for AFF process depend upon the geometry of the gear, a special fixture was designed by **Petare and Jain (2018b)**, consisted two cylindrical parts having circumferential holes as shown in Figure 3.7 for facilitating the forward and backward movement of AFF medium over the flank surfaces of the two consecutive teeth of the spur gear to finish them along the entire face width. It causes shearing off the surface peaks from flank surfaces of gear teeth reducing errors in microgeometry and improves surface roughness. Metalon (a polymer) was used to make the fixture due to its non-reacting nature with the AFF medium and ease of machining.

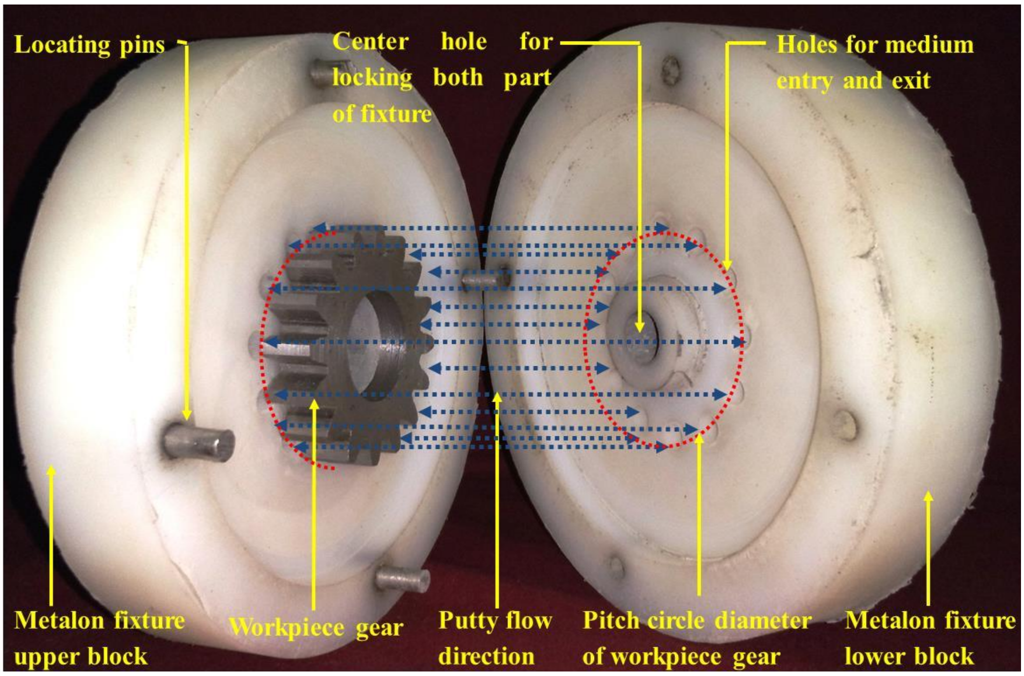



**Figure 3.7:** Fixture used for abrasive flow finishing (AFF) of the spur gears developed by **Petare and Jain (2018b)**.

### 3.3.3 Components of AFF Experimental Apparatus

The AFF apparatus, shown in Fig. 3.8, has two hydraulic cylinders, two AFF medium-containing cylinders, workpiece fixture, two 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.

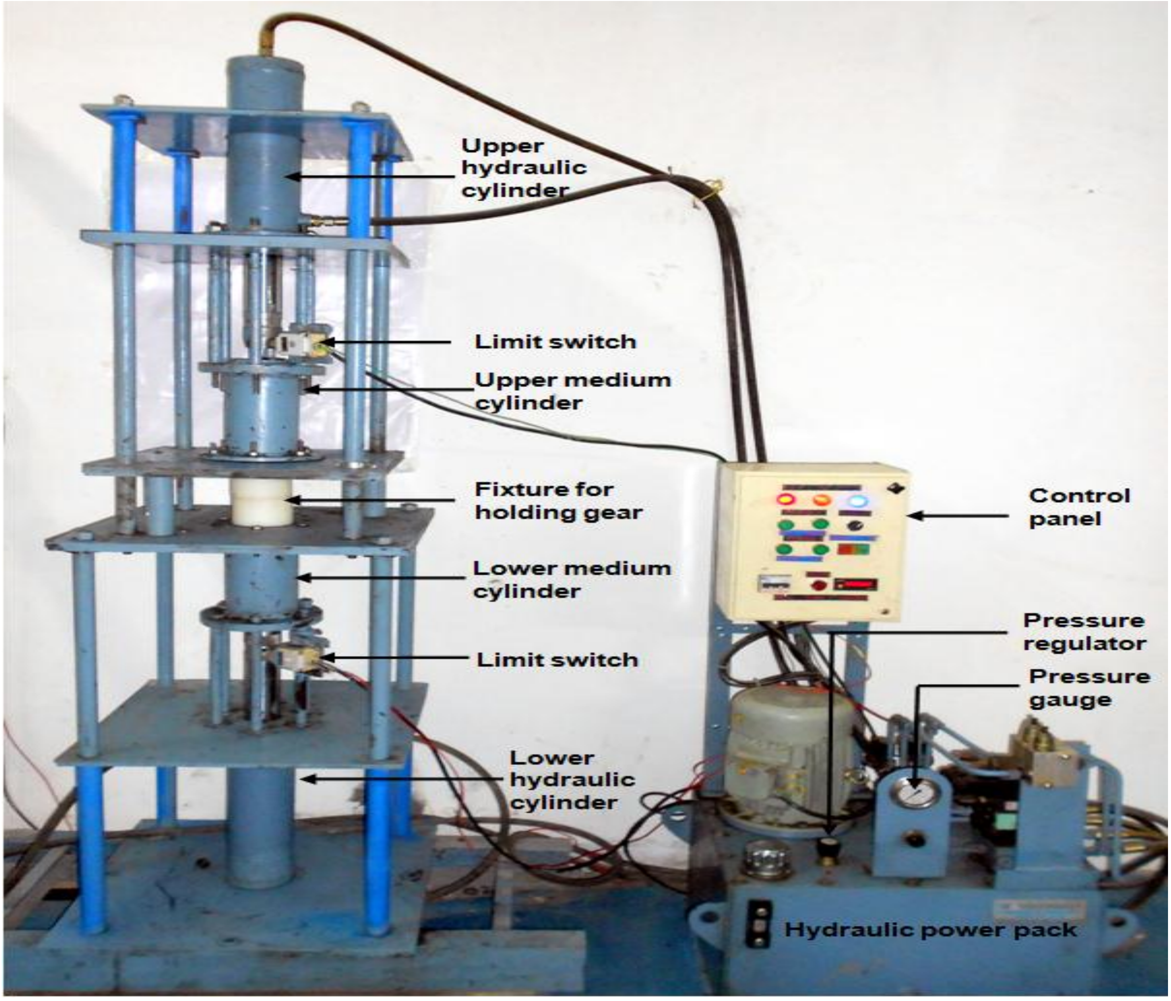



**Figure 3.8:** Photograph of the AFF apparatus developed for gear finishing by **Petare and Jain (2018b)** at IIT Indore.

### 3.3.4 AFF Medium

AFF medium is mixture of shear thickening polymer having self-deforming ability which is loaded with a definite quantity of abrasives and blending oil. The abrasives are chosen according to type and hardness of the workpiece material. Therefore, Silicon Carbide was chosen as abrasive to finish 20MnCr5 of 55HRC. It is prepared by mixing it with long chain polymer based putty and silicon oil for proper blending. Before performing the experiments, the prepared AFF medium was used for 35-40 cycles on workpiece to ensure proper mixing of ingredients **(Petare and Jain, 2018b).**

### 3.3.5 Parameters Used in Finishing of Spur Gears by AFF

Three hobbed spur gears directly and three lasers lay profile spur gears (i.e. six experiments) were finished using the optimum values of AFF parameters identified by **(Petare and Jain, 2018b).** These values are: 5 MPa as extrusion pressure; 100 mesh (i.e.

avg. diameter $d_g$ 50 as size of abrasives); 30 (wt. %) as gravimetric concentration of abrasives in the AFF medium; and 15,20 and 25 minutes as finishing time.

### 3.3.6 Procedure of Spur Gear Finishing 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) 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 in the corresponding fixture and ensuring that there is no rotation of gear in the fixture and axis of the gear 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 to avoid its rusting due to exposure to putty in the finishing fixture.
- All the considered responses were measured for the all the hobbed gears directly finished by AFF and laser lay profile hobbed gear finished by AFF process.

## 3.4 Evaluation of Responses

### 3.4.1 Measurement of Microgeometry

Microgeometry parameters were measured on computer numerically controlled (CNC) gear metrology machine (Smart Gear 500 from *Wenzel Gear Tec, Germany*). Total profile and total lead error, measurements were taken on left-hand and right-hand flanks of randomly chosen four teeth of spur gears before and after their finishing by AFF process. Whereas, cumulative pitch error and runout, measurement were taken on LH and RH of all the 16 teeth of spur gears. Arithmetic mean of the measured values of a microgeometry parameter were used for computing average percentage improvement in that parameter except that of runout i.e. average percentage improvement in the total profile error *'$PIF_a$'* was calculated using Eq. 3.1.

$$Avg\ PIFa = \frac{Avg\ Fa\ values\ before\ AFF\ - Avg\ Fa\ values\ after\ AFF}{Avg\ Fa\ values\ before\ AFF} 100\% \quad (3.1)$$

Similarly, average values of percentage improvement in total lead error '*$PRF_b$*' and percentage improvement in total pitch error '*$PRF_p$*' were calculated. Values of runout before and after finishing by AFF were used to calculate percentage improvement in the runout *'$PIF_r$'* by using Eq. 3.2

$$Avg.PIFr = \frac{Fr\ values\ before\ AFF\ -\ Fr\ values\ after\ AFF}{Fr\ values\ before\ AFF}\ 100\% \qquad (3.2)$$

### 3.4.2 Measurement of Surface Roughness

Average surface roughness '$R_a$' values of spur gears before and after finishing by AFF were measured on LD-130 (Mar Surf from *Mahr Metrology, Germany*) by tracing 10 µm tip diameter of probe and using 2 mm as evaluation length, 0.8 mm as cut-off length. Measurements were taken at two different locations along the profile, on right hand and left-hand flanks of teeth of a spur gear and arithmetic mean of measured values was used in computing average value of percentage improvement in average surface roughness *'$PRR_a$'* using the Eq. 3.3.

$$Avg.PIR_a = \frac{Avg.\ R_a\ value\ before\ AFF - Avg.\ R_a value\ after\ AFF}{Avg.\ R_a\ value\ before\ AFF} 100\ (\%) \quad (3.3)$$

Similarly, average percentage improvement in maximum surface roughness '*$PIR_{max}$*' was calculated.

### 3.4.3 Measurement of Wear Resistance

Reciprocating tribo-test was performed using fretting tribometer CM-9104 (from *Ducom, India*) on the randomly selected one tooth of the (i) hobbed spur gear, (ii) the best finished hobbed spur gear directly by AFF, and (iii) AFF finished laser lay profiled hobbed spur gear. The photograph of tribometer with test specimen is shown in Fig. 3.9. The specimen was prepared by cold mount of the selected gear tooth for fixing it in the vise of the tribometer. Bottom surface of the cold mount was faced on a lathe machine to keep top surface of gear tooth perfectly parallel to surface of stainless steel ball. A load of 50 N was applied over 5 mm diameter stainless steel ball and it was made to slide over the flank surface of the selected spur gear tooth. Sliding distance of 5 mm and frequency of 20 Hz was used as per ASTM G133–05. Wear rate calculated by using following relation given by Archard's.

$$k = \frac{V}{Fs}(mm^3/\text{Nm}) \quad (3.4)$$

Where $k$ is specific wear rate ($mm^3$/Nm); $V$ is the wear volume ($mm^3$); $F$ is the applied load (N); and $s$ is the sliding distance (m). A precision weight balance having least count of 0.01 mg used to calculate mass loss in the wear test.

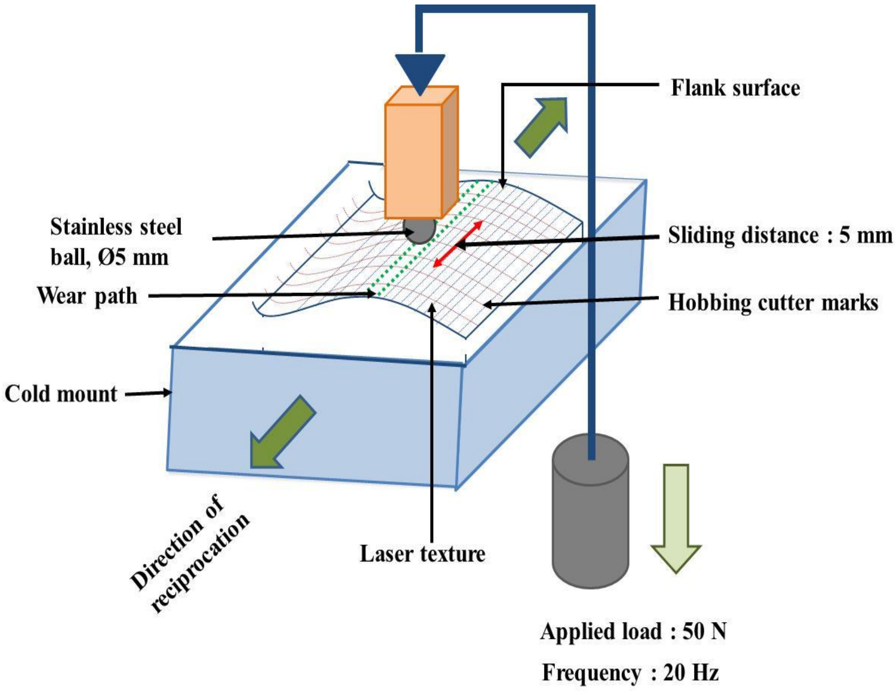



**Figure 3.9:** Schematic of the fretting wear test performed on the spur gear tooth.

### 3.4.4 Measurement of Microhardness

Microhardness values of (i) hobbed spur gear, (ii) the best-finished hobbed spur gear directly by AFF, and (iii) AFF finished laser lay profiled hobbed spur gear were measured at load of 50; 100; 200 (gm) respectively for a time of 15 second by using microhardness tester VMH-002 (from *Walter UHL, Germany*). Three indentations for each value of the applied load were taken and average of these values taken for investigation.

# Chapter 4

## Results and Discussions

This chapter describes the comparison of the results of surface roughness, microgeometry, microhardness and wear test of hobbed spur gear with laser lay profiling finished by AFF process and hobbed spur gear without laser lay profiling finished by AFF process.

### 4.1 Results of Surface Roughness

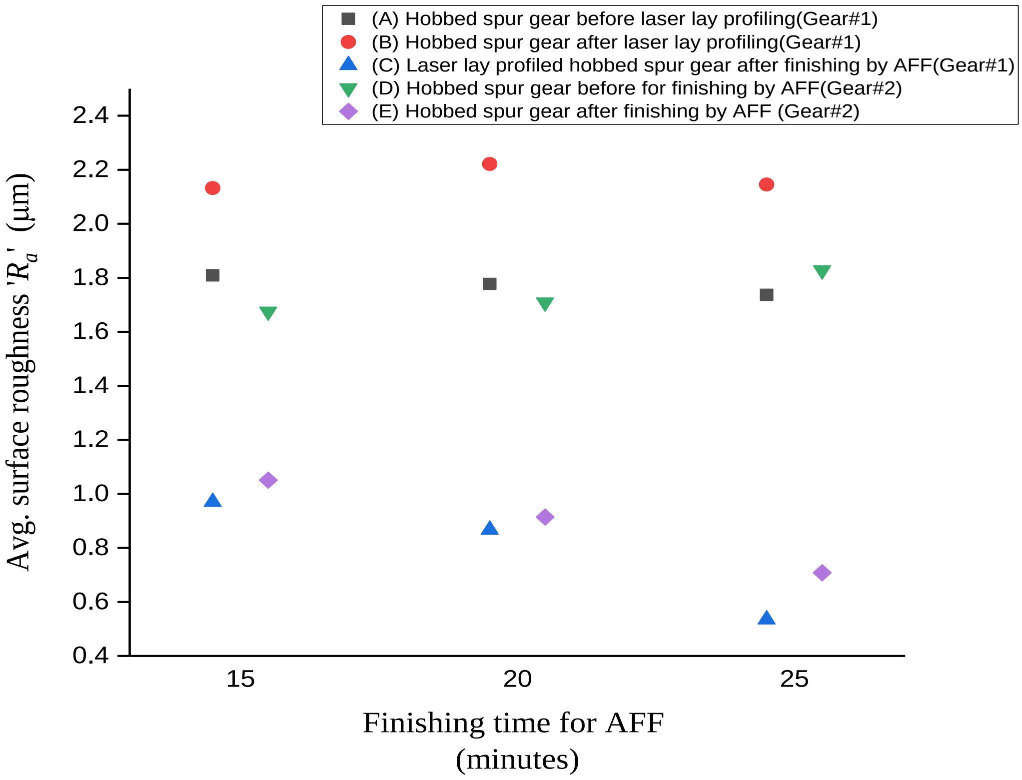
Table 4.1 presents results for average and maximum surface roughness values for different processing condition of the hobbed gear. It depicts that the average surface roughness and maximum surface roughness ($R_a$ and $R_{max}$) after finishing by AFF considerably reduced from 1.74 to 0.53 µm and 12.94 to 4.02 µm respectively for hobbed spur gear with laser lay profiling and from 1.83 to 0.71 µm and 12.79 to 6.64 µm respectively for hobbed spur gear without laser lay profiling with finishing time of 25 minutes.

Fig.4.1(a) depicts the absolute values of average surface roughness '$R_a$' of different processing condition of spur gears with different finishing time (i.e. 15,20,25 minutes). Fig.4.1(b) depicts the variation in percentage improvement in Avg. '$R_a$' for finishing of hobbed spur gear with laser lay profiling and hobbed spur gear without laser lay profile by AFF process with different finishing time (i.e. 15,20,25 minutes).

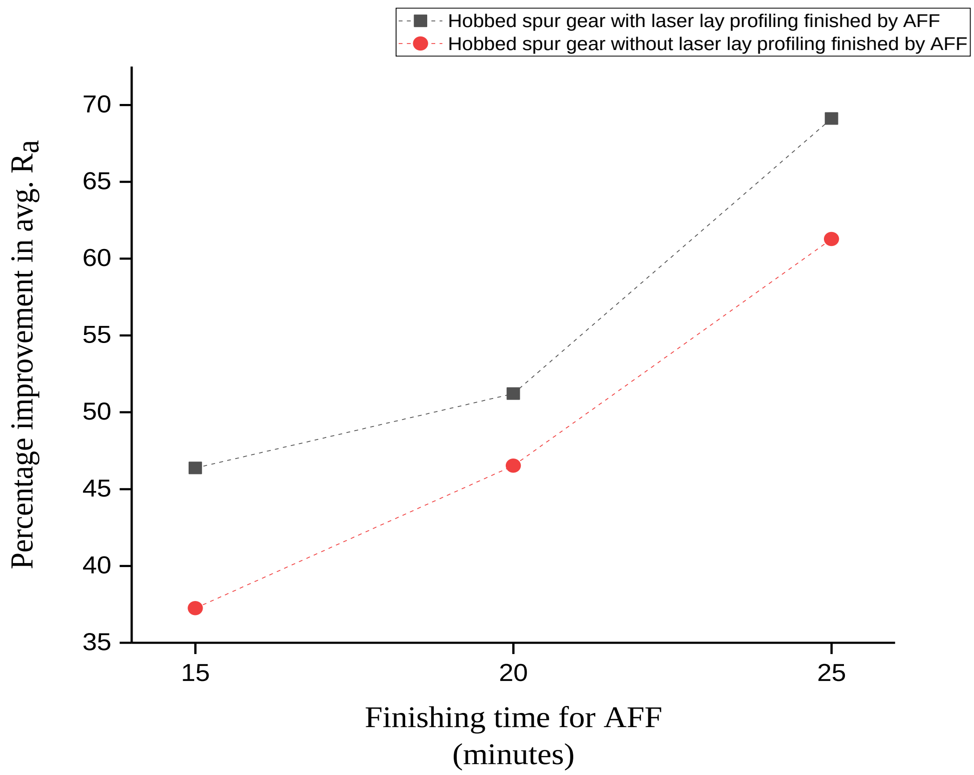
Fig.4.2(a) describes absolute values of maximum surface roughness '$R_{max}$' of different processing condition of spur gears with different finishing time (i.e. 15, 20 and 25 minutes). Fig.4.2(b) depicts the variation in '$PIR_{\mathrm{max}}$' of hobbed spur gear with laser lay profile finished by AFF process and hobbed spur gear without laser lay profile finished by AFF process with different finishing time (i.e. 15,20,25 minutes). It is evident from the fig.4.1(b) and 4.2(b) that the '$PIR_{\mathrm{a}}$' and '$PIR_{\mathrm{max}}$' with finishing time is more for Laser lay profiled hobbed spur gear than the hobbed spur gear without laser lay profile finished by AFF. The maximum '$PIR_{\mathrm{a}}$' and '$PIR_{\mathrm{max}}$' is 69.12% ,68.92% respectively for hobbed spur gear with laser lay profiling, finished by AFF is more as compared to 61.27% ,48.14% respectively for hobbed spur gear without laser lay profile finished by AFF process with finishing time of 25 minutes.

**Table 4.1:** Results of average and maximum surface roughness values for different processing condition of the spur gears.

| Processing condition of the spur gear | | Flank | Finishing time for AFF (minutes) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 15 | | 20 | | 25 | |
| | | | $R_a$ (µm) | $R_{max}$ (µm) | $R_a$ (µm) | $R_{max}$ (µm) | $R_a$ (µm) | $R_{max}$ (µm) |
| **A** | Hobbed gear **before** laser lay profiling (Gear #1) | Left Flank | 1.95 | 12.72 | 1.95 | 14.87 | 1.87 | 12.75 |
| | | Right Flank | 1.66 | 12.90 | 1.6 | 15.10 | 1.6 | 13.13 |
| | | Avg. | 1.81 | 12.81 | 1.77 | 14.98 | 1.74 | 12.94 |
| **B** | Hobbed gear **after** laser lay profiling (Gear #1) | Left Flank | 2.26 | 15.12 | 2.36 | 16.11 | 2.27 | 13.57 |
| | | Right Flank | 1.99 | 14.07 | 2.08 | 16.18 | 2.02 | 15.61 |
| | | Avg. | 2.13 | 14.59 | 2.22 | 16.15 | 2.14 | 14.59 |
| **C** | Laser lay profiled hobbed gear **after** finishing by AFF (Gear #1) | Left Flank | 1.07 | 7.81 | 0.91 | 8.37 | 0.56 | 4.57 |
| | | Right Flank | 0.87 | 8.39 | 0.82 | 6.24 | 0.50 | 3.47 |
| | | Avg. | 0.97 | 8.09 | 0.87 | 7.31 | 0.53 | 4.02 |
| **D** | Hobbed gear **before** for finishing by AFF (Gear #2) | Left Flank | 1.72 | 11.82 | 1.78 | 12.71 | 1.88 | 12.46 |
| | | Right Flank | 1.63 | 11.52 | 1.63 | 12.75 | 1.78 | 13.13 |
| | | Avg. | 1.67 | 11.67 | 1.71 | 12.73 | 1.83 | 12.79 |
| **E** | Hobbed gear **after** finishing by AFF (Gear #2) | Left Flank | 1.15 | 9.02 | 0.92 | 7.18 | 0.76 | 6.58 |
| | | Right Flank | 0.95 | 8.13 | 0.90 | 7.06 | 0.65 | 6.69 |
| | | Avg. | 1.05 | 8.58 | 0.91 | 7.12 | 0.71 | 6.64 |
| Percentage improvement in Avg. $R_a$ value of the hobbed gear by AFF **with laser lay profiling** (%) (Gear # 1) | | [(A-C)/A]100% | 46.37 | 36.79 | 51.21 | 51.23 | 69.12 | 68.92 |
| Percentage improvement in Avg. $R_a$ values of the hobbed gear by AFF **without laser lay profiling** (%) (Gear #2) | | [(D-E)/D]100% | 37.25 | 26.51 | 46.52 | 44.06 | 61.27 | 48.14 |

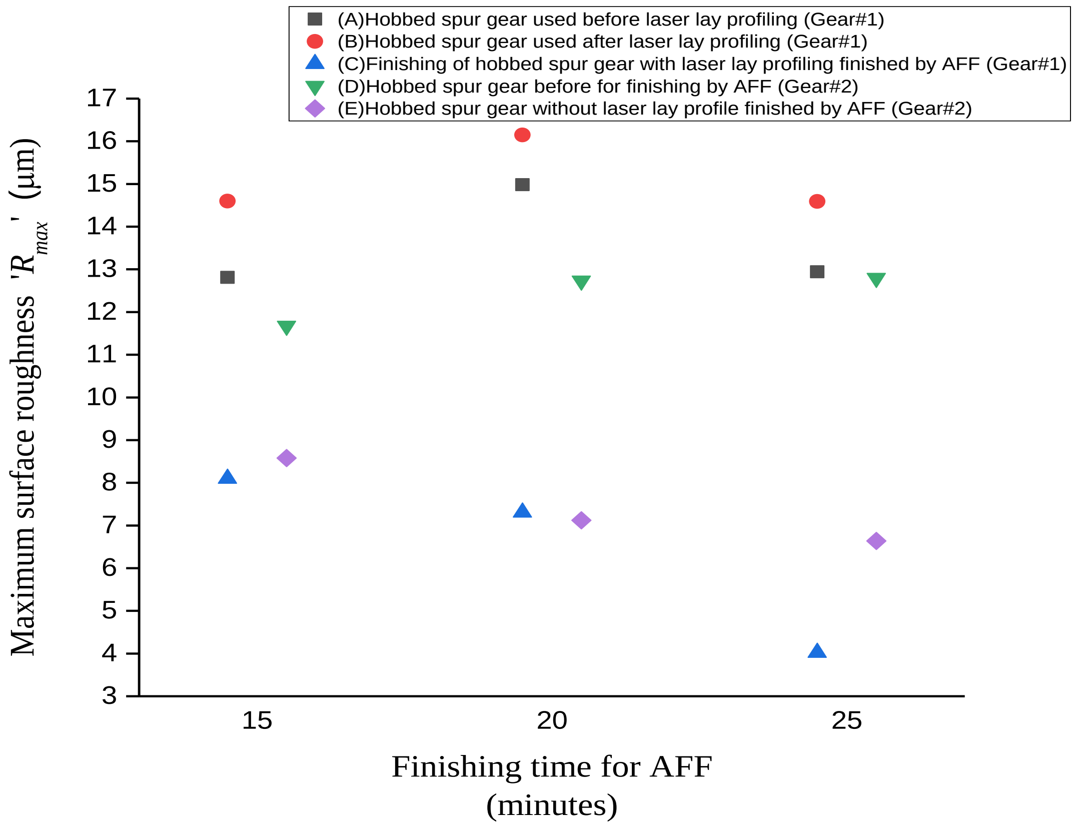



**(a)**

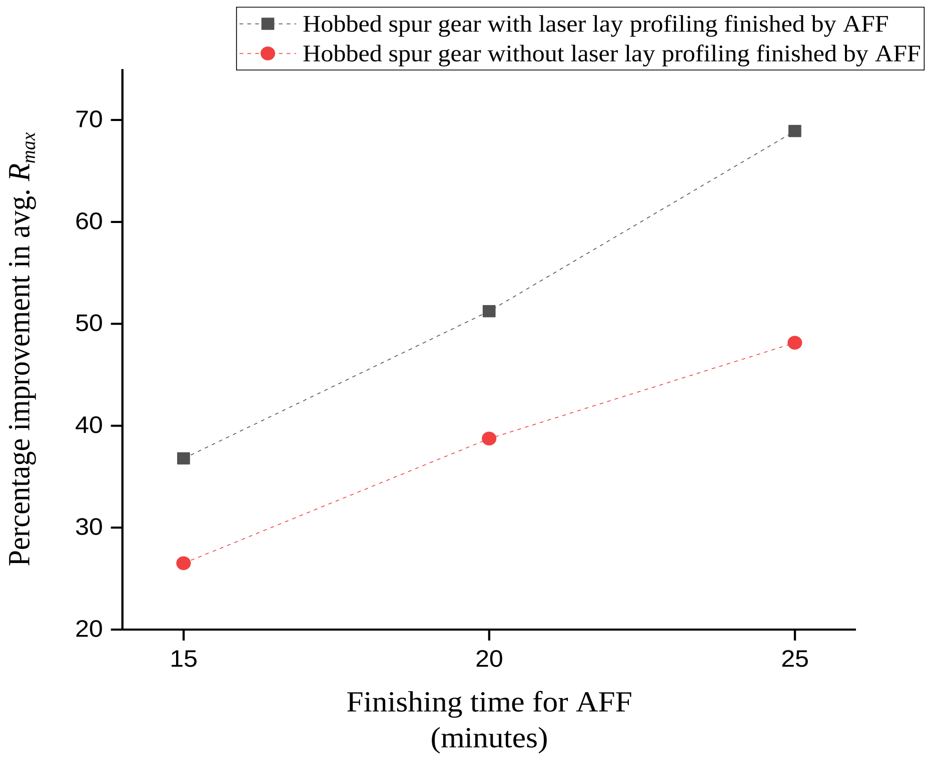



**(b)**

**Figure 4.1:** (a) Absolute values of avg. $R_a$, (b) percentage improvement in avg. $R_a$ with different finishing time of 15, 20, 25 minutes.




**(a)**




**(b)**

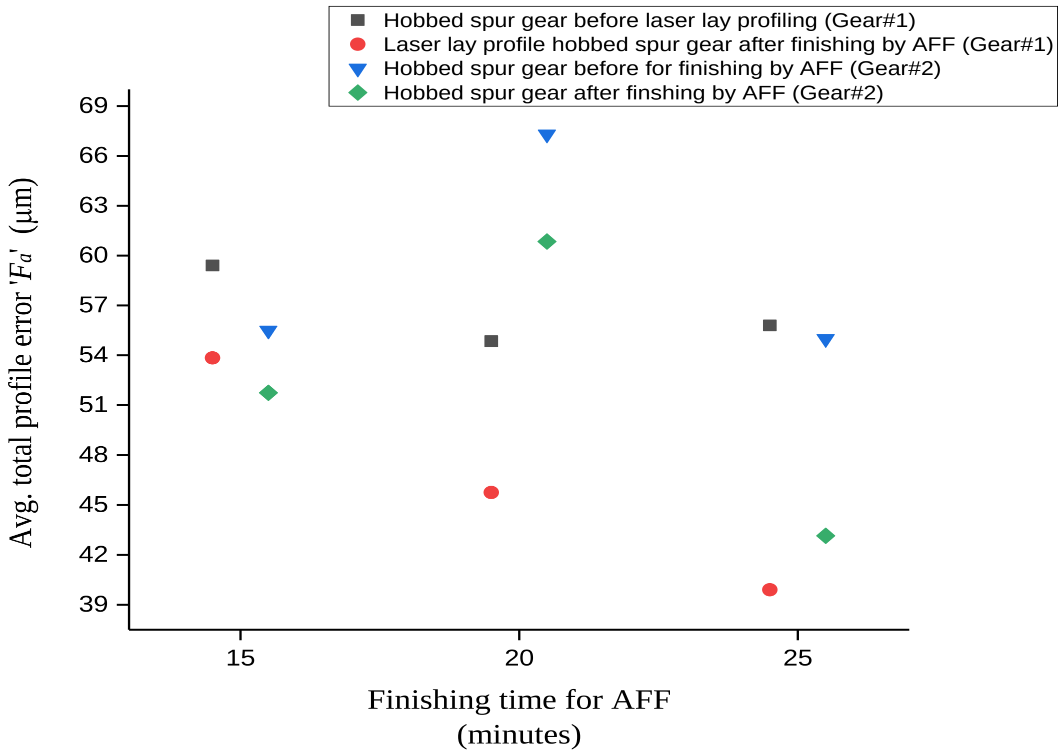
**Figure 4.2:** (a) Absolute values of avg. $R_{max}$, (b) Percentage improvement in avg. $R_{max}$ with different finishing time of 15,20,25 minutes.

## 4.2 Results of Microgeometry

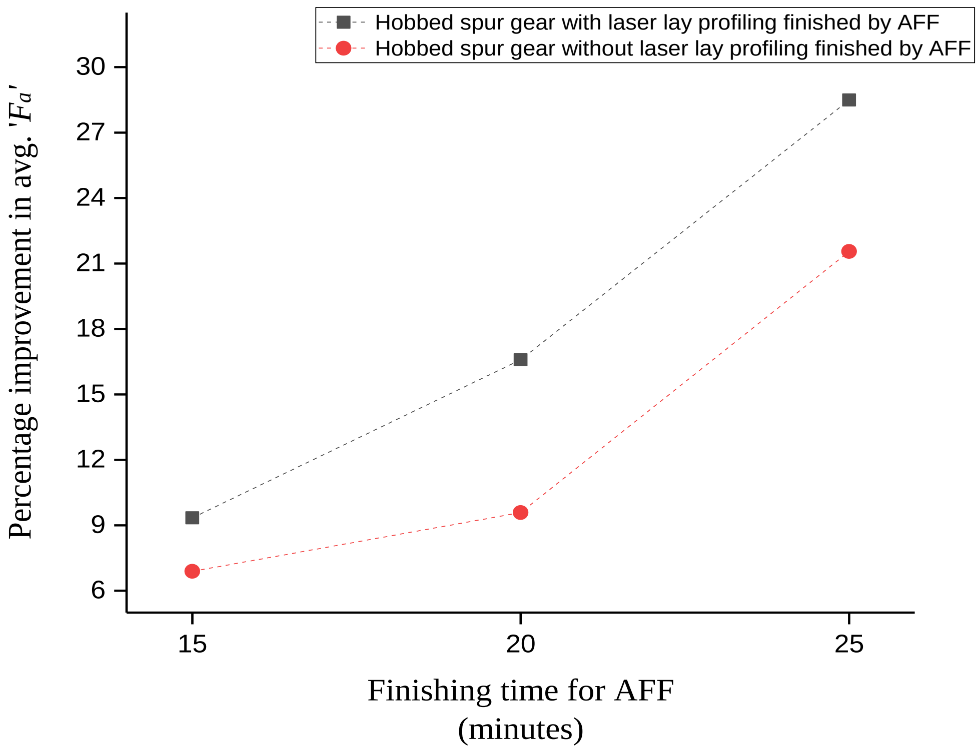
Table 4.2 presents the results of total profile error, total lead error, cumulative profile error and runout error for different processing condition of hobbed spur gear. Avg. values of total profile error ($F_a$), total lead error ($F_\beta$) and cumulative pitch error ($F_P$) for hobbed spur gear with laser lay profiling with finishing time of 25 minutes were dropped from 55.80 to 39.90 µm; 24.5 to 14.65 µm; and 117.1 to 88.7 µm respectively after its finishing by the AFF process. The quality of gear improved from DIN 12 to DIN 11; DIN 10 to DIN 9; and DIN 12 to DIN 11 respectively in these aspects of deviation. Runout ($F_r$) value reduced from 179 to 170.4 µm without changing quality of gear. Similarly, Avg. values of total profile error ($F_a$), total lead error ($F_\beta$) and cumulative pitch error ($F_P$) for hobbed spur gear without laser lay profiling were dropped from 55 to 43.15 µm; 22.45 to 13.7 µm; and 106.55 to 89.55µm respectively after its finishing by the AFF process. The quality of gear improved from DIN 12 to DIN 11; DIN 11 to DIN 10; and DIN 12 to DIN 11respectively in these aspects of deviation. Runout ($F_r$) value reduced from 171 to 163.7 µm without. changing the quality of gear.

**Table 4.2:** Results of microgeometry values for the different processing condition of the spur gears

| Processing condition of the spur gear | Flank | Finishing time for AFF (minutes) (μm) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **15** | | | | **20** | | | | **25** | | | |
| | | $F_a$ | $F_b$ | $F_P$ | $F_r$ | $F_a$ | $F_b$ | $F_P$ | $F_r$ | $F_a$ | $F_b$ | $F_P$ | $F_r$ |
| **A** Hobbed gear **before** laser lay profiling (Gear #1) | Left | 57.40 | 34.9 | 76.3 | 175.6 | 63.50 | 39.7 | 113.6 | 177.3 | 57.90 | 21.3 | 148.6 | 179 |
| | Right | 61.40 | 38.8 | 153.4 | | 46.20 | 49.5 | 158.3 | | 53.70 | 27.7 | 85.6 | |
| | Avg. | 59.40 | 36.85 | 114.85 | | 54.85 | 44.6 | 135.95 | | 55.80 | 24.5 | 117.1 | |
| | DIN | 12 | 11 | 12 | >12 | 12 | 12 | 12 | >12 | 12 | 10 | 12 | >12 |
| **B** Laser lay profiled hobbed gear **after** finishing by AFF (Gear #1) | Left | 47.60 | 30.8 | 131.4 | 172.2 | 52.10 | 29.8 | 73.2 | 171.2 | 40.40 | 13 | 99.9 | 170.4 |
| | Right | 60.10 | 34.3 | 84.3 | | 39.40 | 34.9 | 138.7 | | 39.40 | 16.3 | 77.5 | |
| | Avg. | 53.85 | 32.55 | 107.85 | | 45.75 | 32.35 | 105.96 | | 39.90 | 14.65 | 88.7 | |
| | DIN | 12 | 11 | 11 | >12 | 11 | 11 | 12 | >12 | 11 | 9 | 10 | >12 |
| **C** Hobbed gear **before** for finishing by AFF (Gear #2) | Left | 51.40 | 39.8 | 149.4 | 168.1 | 65.60 | 36.5 | 171 | 129.8 | 65.80 | 21.9 | 122.4 | 171 |
| | Right | 59.60 | 49.7 | 122.9 | | 69.00 | 42.3 | 122.9 | | 44.20 | 23 | 90.7 | |
| | Avg. | 55.50 | 44.75 | 136.15 | | 67.30 | 39.4 | 146.95 | | 55.00 | 22.45 | 106.5 | |
| | DIN | 12 | 12 | 12 | >12 | 12 | 12 | 12 | >12 | 12 | 10 | 12 | >12 |
| **D** Hobbed gear **after** finishing by AFF (Gear #2) | Left | 47.00 | 33.1 | 155.1 | 166 | 59.80 | 30.2 | 137.1 | 126.4 | 49.20 | 17.2 | 121.4 | 163.7 |
| | Right | 56.50 | 48 | 109.8 | | 61.90 | 32.8 | 123.7 | | 37.10 | 10.2 | 57.7 | |
| | Avg. | 51.75 | 40.55 | 132.45 | | 60.85 | 31.5 | 130.4 | | 43.15 | 13.7 | 89.55 | |
| | DIN | 12 | 12 | 12 | >12 | 12 | 11 | 12 | >12 | 11 | 9 | 11 | >12 |
| Percentage improvement of the hobbed gear by AFF **with laser lay profiling** (%) (Gear # 1) | [(A-B)/A]100% | 9.34 | 11.67 | 6.09 | 1.94 | 16.59 | 27.47 | 15.64 | 3.44 | 28.49 | 40.2 | 24.85 | 4.80 |
| Percentage improvement in of the hobbed gear by AFF **without laser lay profiling** (%) (Gear #2) | [(C-D)/C]100% | 6.89 | 9.08 | 2.71 | 1.24 | 9.58 | 20.05 | 11.26 | 2.62 | 21.55 | 38.97 | 15.95 | 3.93 |

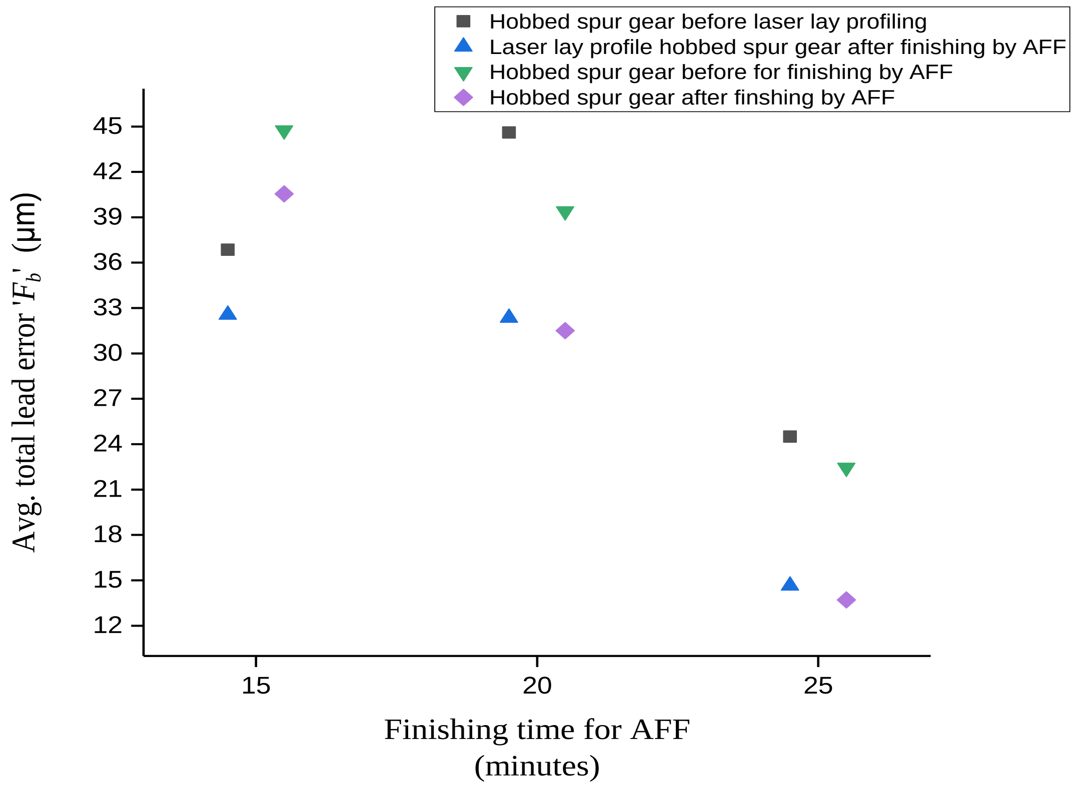



**(a)**

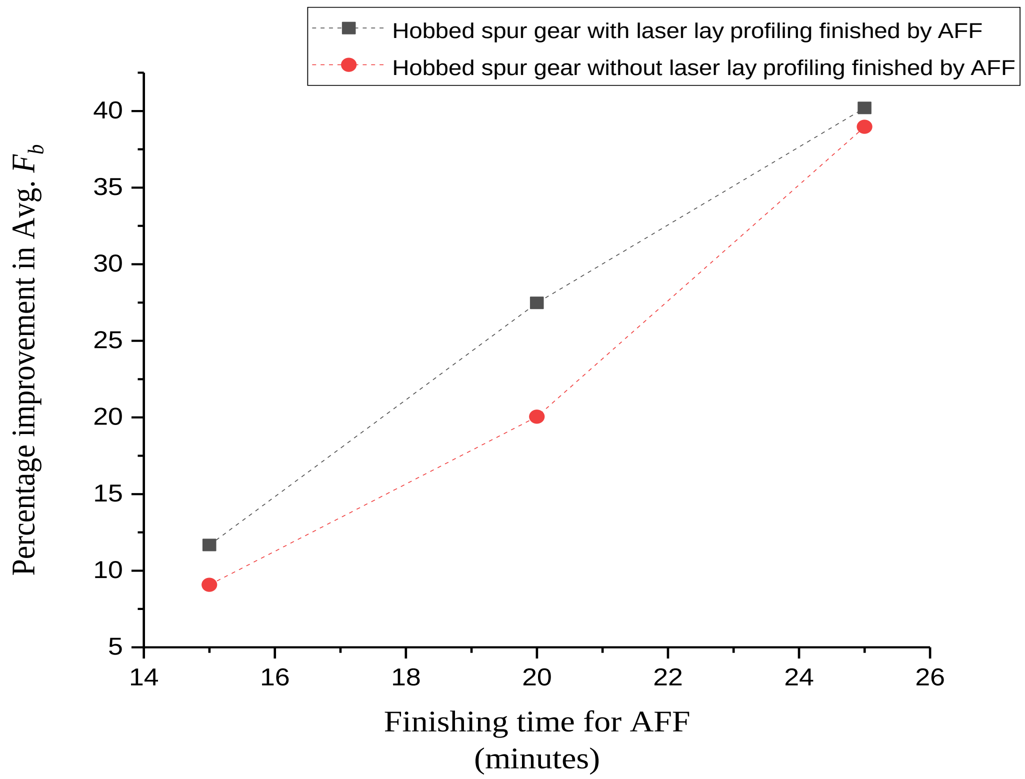



**(b)**

**Figure 4.3:** (a) Absolute values of Avg. $F_a$, (b) percentage improvement in Avg. $F_a$ with different finishing time of 15,20,25 minutes.

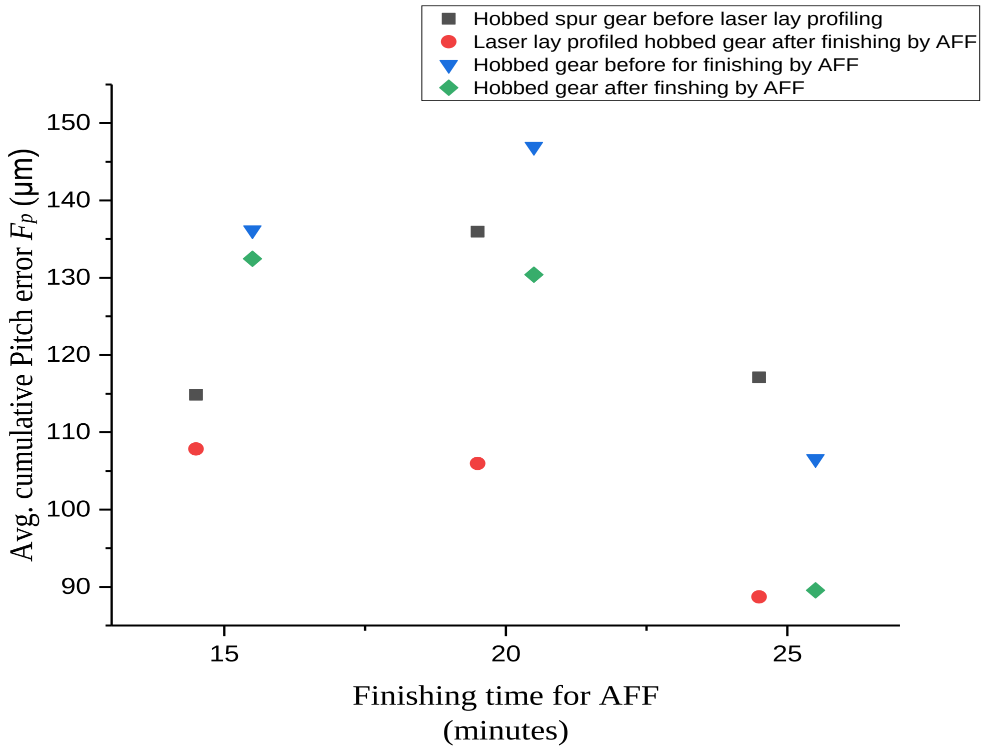



**(a)**




**(b)**

**Figure 4.4:** (a) Absolute values of avg. $F_b$, (b) percentage improvement in avg. $F_b$ with different finishing time of 15,20,25 minutes.

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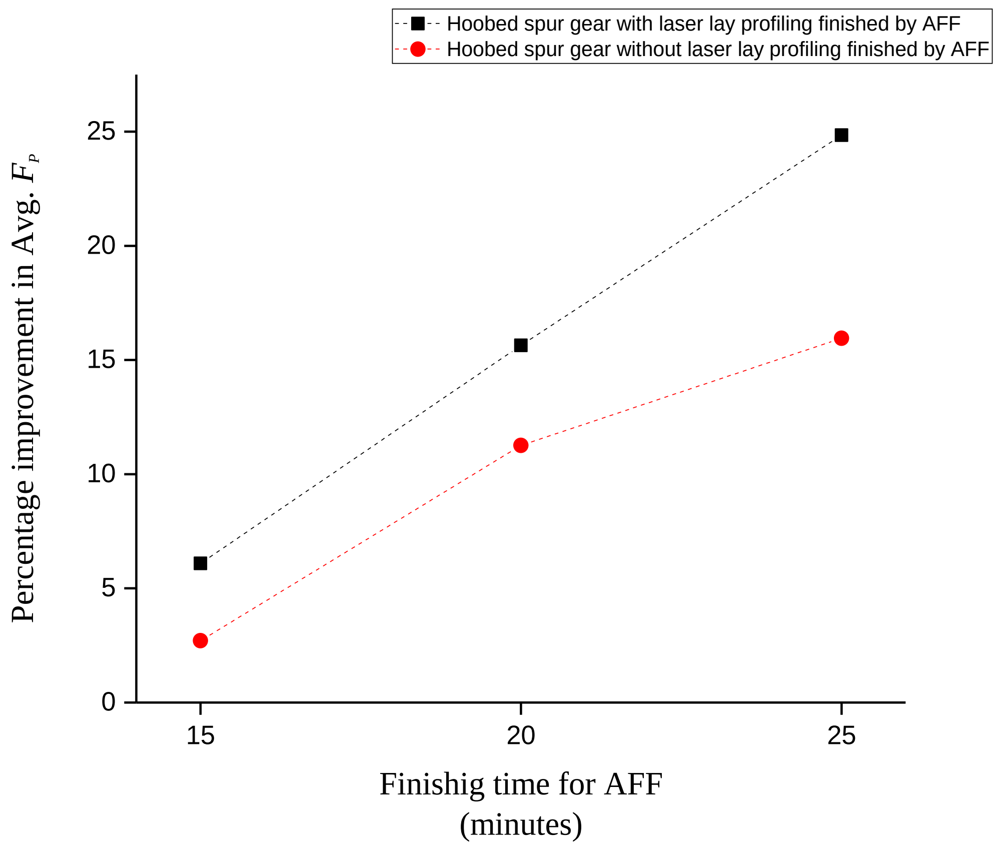
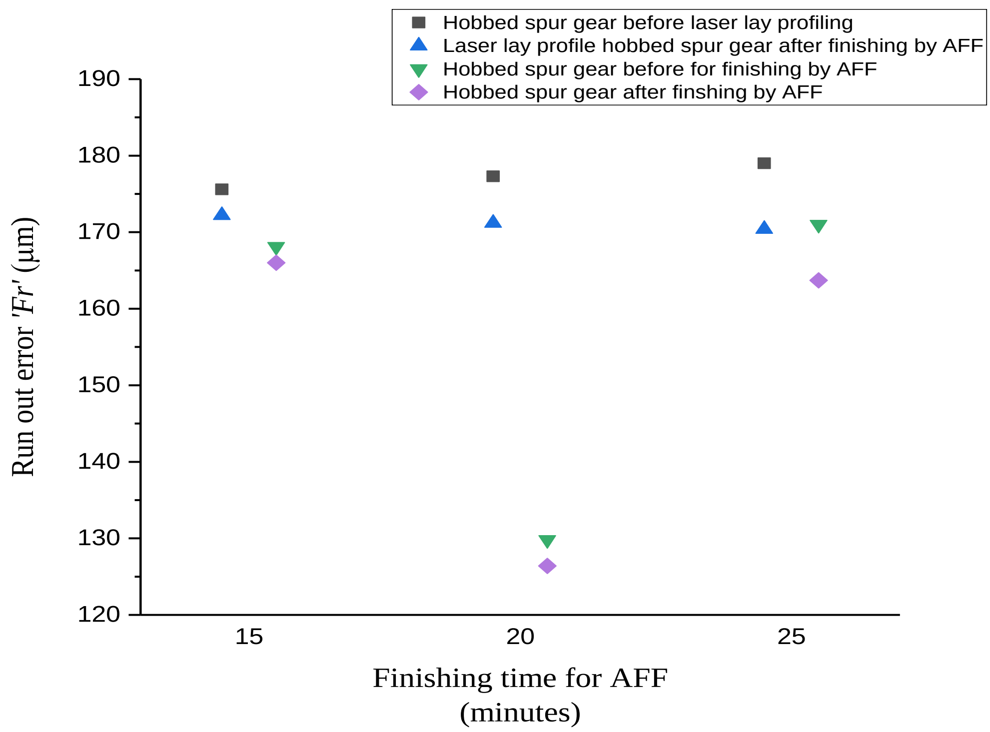
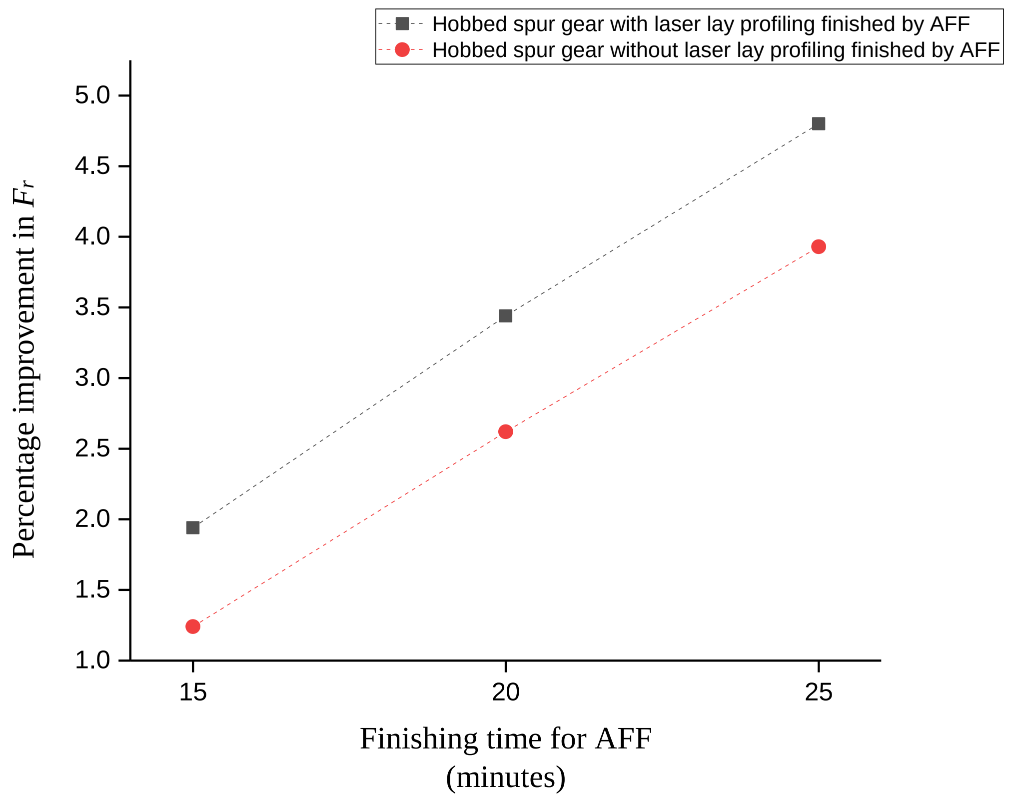



**(b)**

**Figure 4.5:** (a) Absolute values of avg. $F_P$, (b) Percentage improvement in avg. $F_P$ with different finishing time of 15,20,25 minutes.




**(a)**




**(b)**

**Figure 4.6:** (a) Absolute values of avg. $F_r$, (b) Percentage improvement in avg. $F_r$ with different finishing time of 15,20,25 minutes.

Figure 4.3(a) describes absolute values of ‘$F_a$’ of different processing condition of spur gears with different finishing time (i.e. 15, 20 and 25 minutes). Figure 4.3(b) depicts the variation in ‘$PIF_a$’ of laser lay profile hobbed gear finished by AFF process and hobbed gear directly finished by AFF process at different machining time (i.e. 15,20,25 minutes). It is evident from the graph 4.3(b) that the ‘$PIF_a$’ with finishing time is more for Laser profiled gear than the hobbed gear finished by AFF. The maximum ‘$PIF_a$’ is, 28.49% for laser lay profile hobbed spur gear finished by AFF as compared to 21.55% hobbed gear directly finished by AFF process with finishing time of 25 minutes.

Figure 4.4(a) describes absolute values of ‘$F_b$’ of different processing condition of spur gears with different finishing time (i.e. 15, 20 and 25 minutes). Figure 4.4(b) depicts the variation in ‘$PIF_b$’ of laser lay profile hobbed gear finished by AFF process and hobbed gear directly finished by AFF process at different machining time (i.e. 15,20,25 minutes). It is evident from the graph 4.4(b) that the ‘$PIF_b$’ with finishing time is more for Laser profiled gear than the hobbed gear finished by AFF. The maximum ‘$PIF_b$’ is, 40.2% for laser lay profile hobbed spur gear finished by AFF as compared to 38.97% hobbed gear directly finished by AFF process with finishing time of 25 minutes.

Figure 4.5(a) describes absolute values of ‘$F_P$’ of different processing condition of spur gears with different finishing time (i.e. 15, 20 and 25 minutes). Figure 4.5(b) depicts the variation in ‘$PIF_P$’ of laser lay profile hobbed gear finished by AFF process and hobbed gear directly finished by AFF process with different finishing time (i.e. 15,20,25 minutes). It is evident from the graph 4.5(b) that the ‘$PIF_P$’ with finishing time is more for Laser profiled gear than the hobbed gear finished by AFF. The maximum ‘$PIF_P$’ is, 24.85% for laser lay profile hobbed spur gear finished by AFF as compared to 15.95% hobbed gear directly finished by AFF process with finishing time of 25 minutes.

Figure 4.6(a) describes absolute values of ‘$F_r$’ of different processing condition of spur gears with different finishing time (i.e. 15, 20 and 25 minutes). Figure 4.6(b) depicts the variation in ‘$PIF_r$’ of laser lay profile hobbed spur gear finished by AFF process and hobbed spur gear directly finished by AFF process at different machining time (i.e. 15,20,25 minutes). It is evident from the graph 4.6(b) that the ‘$PIF_r$’ with finishing time is more for Laser profiled gear than the hobbed gear finished by AFF. The maximum ‘$PIF_r$’ is, 4.8% for laser lay profile hobbed spur gear finished by AFF as compared to 3.93% hobbed spur gear directly finished by AFF process with finishing time of 25 minutes.

## 4.3 Results of Material Removal Rate

Table 4.3 presents the Material Removal Rate 'MRR' values for different processing conditions of the spur gears.

**Table 4.3:** Results of Material Removal Rate '*MRR*' values for different processing conditions of the spur gears.

| **Processing condition of the spur gear** | | | **Finishing time 'T' for AFF (minutes)** | | |
|---|---|---|---|---|---|
| | | | **15** | **20** | **25** |
| A | Hobbed gear used for laser lay profiling weight (gm) | | 100.18 | 100.58 | 101.01 |
| B | Laser lay profile hobbed gear weight (gm) | | 99.20 | 99.592 | 99.91 |
| C | Laser lay profile hobbed gear finished by AFF weight (gm) | | 98.76 | 98.62 | 98.25 |
| D | Hobbed gear directly used for AFF weight (gm) | | 102.78 | 102.31 | 101.66 |
| E | Hobbed gear directly finished by AFF weight (gm) | | 102.56 | 101.68 | 100.41 |
| | MRR for laser lay profile hobbed gear finished by AFF (gm/min) | [B-C]/T | 0.03 | 0.049 | 0.066 |
| | MRR for hobbed gear directly finished by AFF (gm/min) | [D-E]/T | 0.014 | 0.031 | 0.05 |

Fig.4.7 shows that there is more material removal rate for laser lay profile hobbed spur gear finished by AFF process than the hobbed spur gear directly finished by AFF process**.** MRR is 0.066 gm/min for laser lay profile hobbed spur gear finished by AFF as compared to 0.05 gm/min for hobbed spur gear directly finished by AFF process with finishing time of 25 minutes.

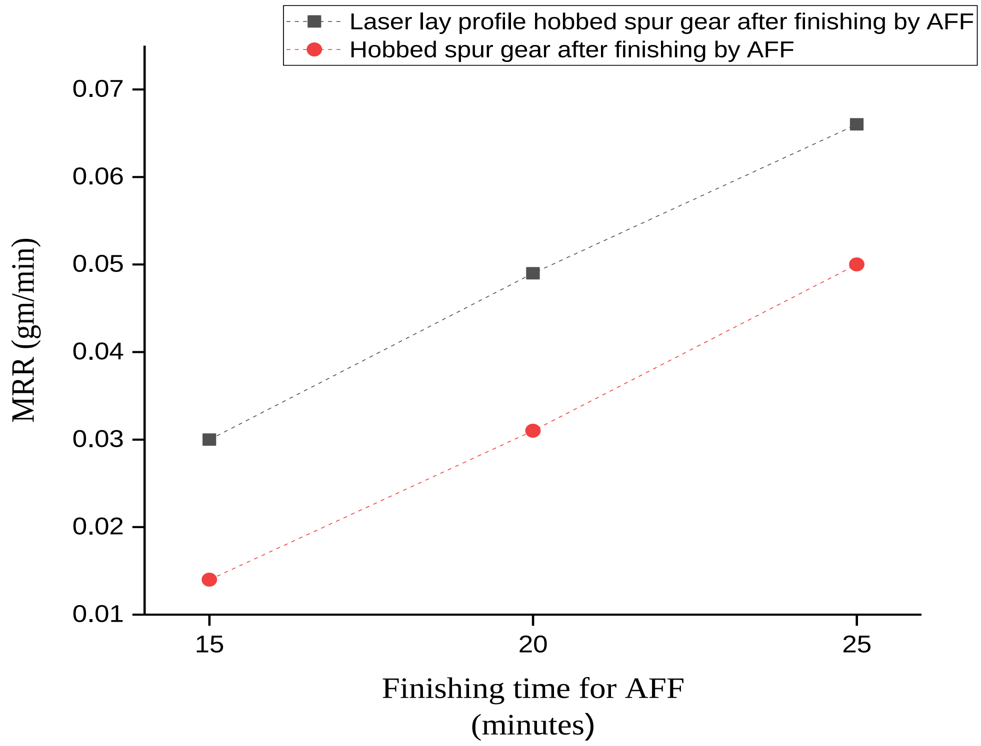



**Figure 4.7:** Material removal rate for different processing condition of gears with different finishing time 15; 20 and 25 minutes.

Fig.4.8. represent finishing mechanism in AFF for hobbed spur gear surface without laser lay profiling (Fig.4.8a); and hobbed spur gear with laser lay profiling (Fig.4.8b). On comparing improvement rate of average surface roughness '$PIR_a$', maximum surface roughness '$PIR_{max}$' total profile error '$PIF_a$', total lead error '$PIF_\beta$', total pitch error '$PIF_p$', runout error '$PIF_r$', and material removal rate '*MRR*' in both the cases after finishing by AFF. More improvement observed in hobbed spur gear with laser lay profile after finishing by AFF. For finishing of hobbed spur gear surface without laser lay profiling by AFF, abrasive particles reciprocate over the flank surface and follow straight path along the lay profile generated due to hobbing and travel very short path while flowing of medium. Therefore, less number of surface roughness peaks comes in active abrasive particle and improvement rate is less (Fig.4.8a). Whereas for finishing of hobbed spur gear with laser lay profiling by AFF. Homothetic laser texture and hobbed cutter marks formed a mesh like structure which deflect flow direction of abrasives medium and cover more distance and causes uniform abrasion and more material removal rate. As the finishing time increases contact of abrasive particle increases and more improvement observed in average percentage improvements in average surface roughness '$PIR_a$',

maximum surface roughness ‘$PIR_{max}$’ total profile error ’$PIF_a$’, total lead error ‘$PIF_\beta$’, total pitch error ‘$PIF_p$’, runout error ‘$PIF_r$’, and material removal rate ‘*MRR*’ with same finishing time.

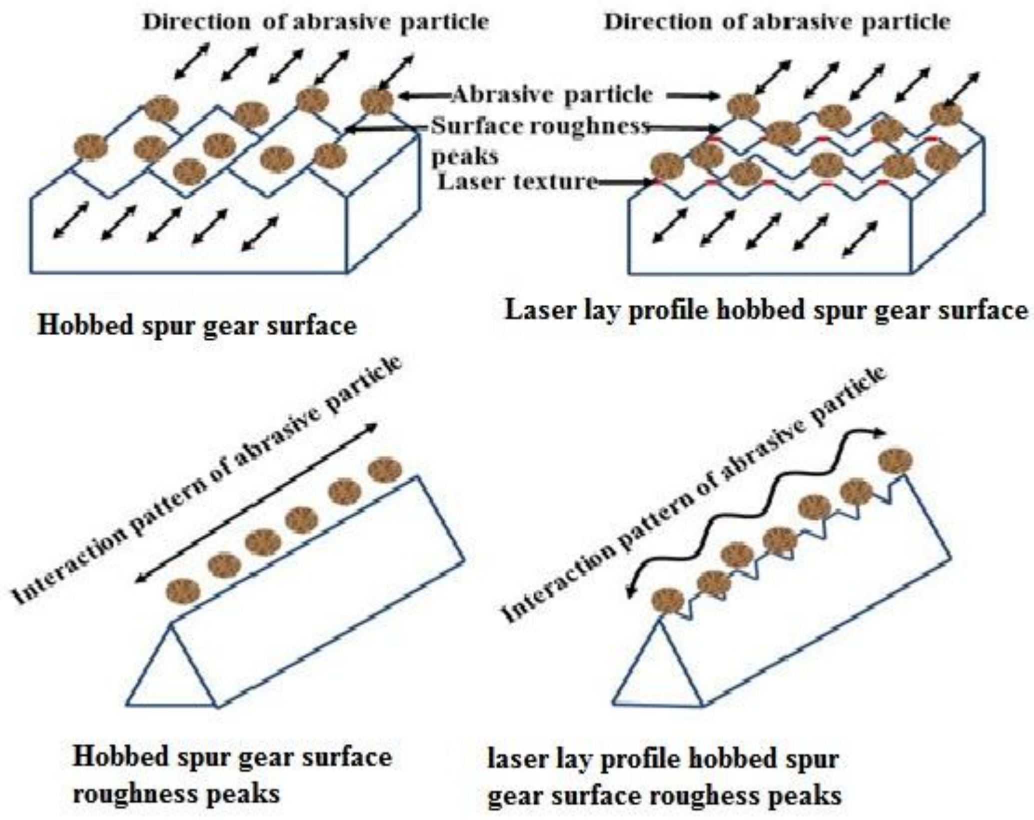



**Figure 4.8**: schematic of interaction pattern of abrasives with surface roughness peaks of hobbed spur gears and laser lay profile hobbed spur gears during AFF process.

## 4.4Analysis of Microhardness

**Table 4.4:** Results of microhardness evaluation of the hobbed spur gear before finishing and the best finished hobbed spur gear and laser lay profile hobbed spur gear by AFF process.

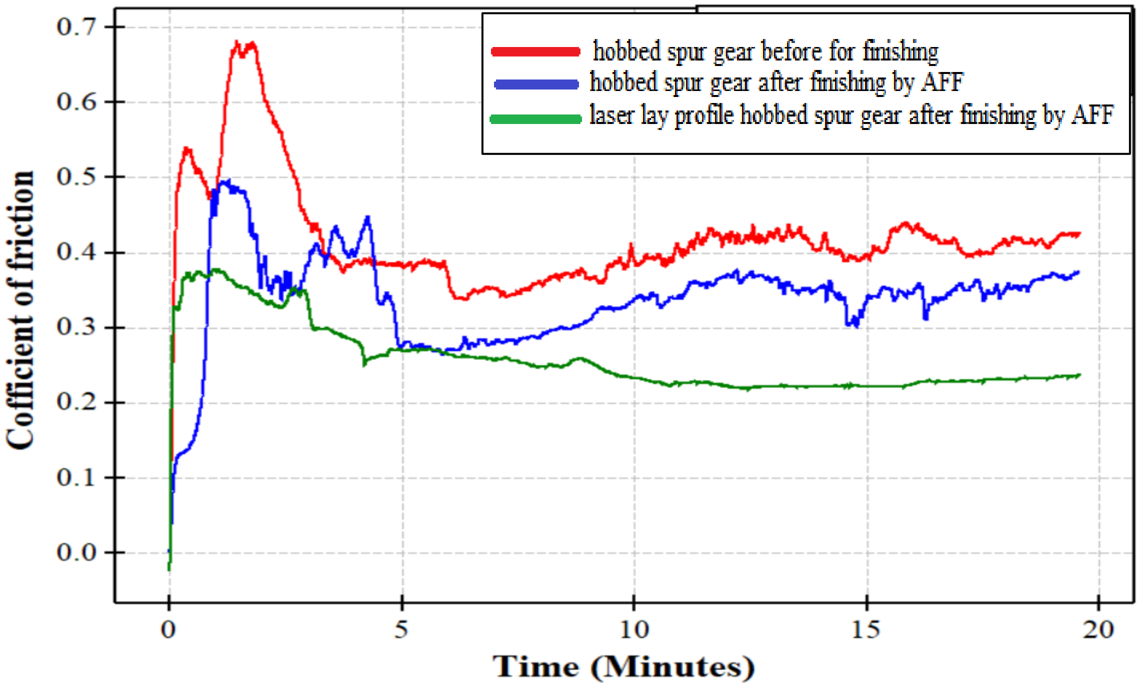
| Parameter name (unit) | Before finishing | | | Best finished | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Hobbed spur gear | | | Hobbed spur gear | | | Laser lay profile hobbed spur gear | | |
| Indentation force (gm) | 50 | 100 | 200 | 50 | 100 | 200 | 50 | 100 | 200 |
| Average microhardness (HV) | 192 | 198 | 204 | 199 | 212 | 214 | 230 | 239 | 241 |

It is observed from Table 4.4 that maximum HV values of average microhardness is 204, 214, 241 at indentation force of 200 gm for hobbed spur gear before for finishing, best finished hobbed spur gear and laser lay profile hobbed spur gear by AFF, respectively. High improvement in Average microhardness of laser lay profile hobbed spur gear observed compared to hobbed spur gear because of residual stresses generated due to laser texturing and AFF applies high extrusion pressure over the finishing medium to flow over the unfinished surface in back and forth direction.

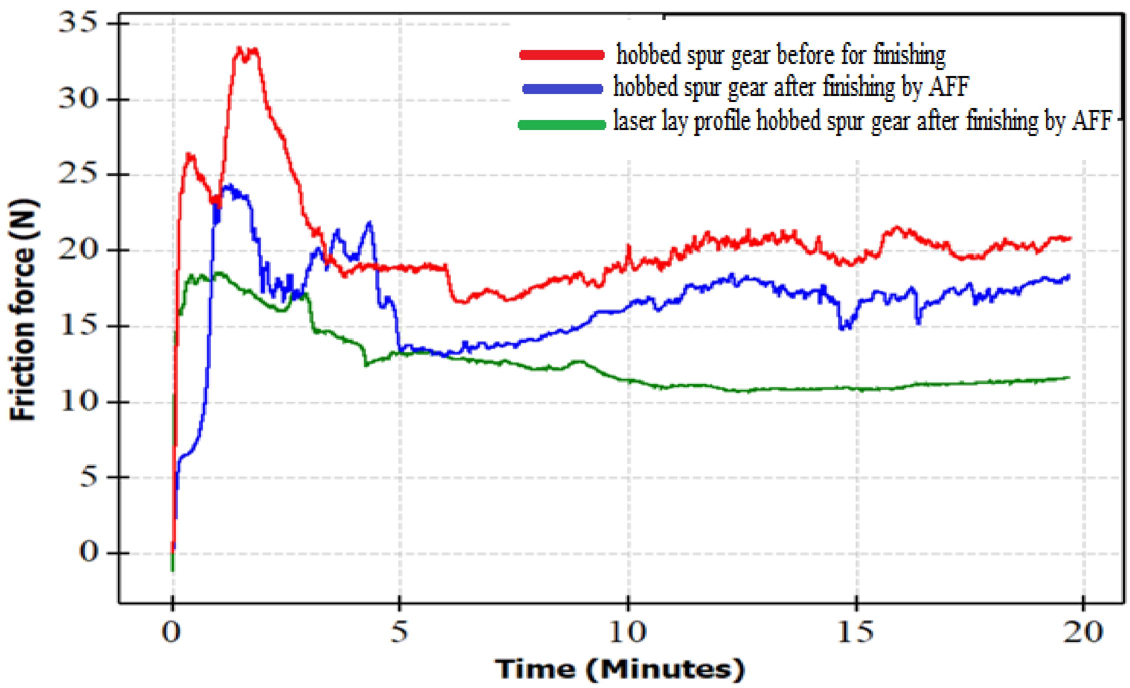
## 4.5 Analysis of Fretting Wear Test

**Table 4.5:** Results of fretting wear test for the hobbed spur gear before finishing and the best finished spur gear by the AFF process.

| **Parameter name (unit)** | **Before finishing** | **Best finished by AFF** | |
|---|---|---|---|
| | Hobbed spur gear | Hobbed spur gear | Laser lay profile hobbed spur gear |
| Max. value of sliding frictional force (N) | 33.48 | 24.35 | 18.64 |
| Max. value of coefficient of sliding friction | 0.683 | 0.497 | 0.379 |
| Specific wear rate '$k_i$' ($mm^3$/N-m) | 14.8 x $10^{-6}$ | 5.73 x $10^{-6}$ | 4.22 x $10^{-6}$ |
| Wear rate ($mm^3$/m) | 7.27 x $10^{-4}$ | 2.81 x $10^{-4}$ | 2.67 x $10^{-4}$ |
| Sliding wear volume '$V_i$' ($mm^3$) | 0.174 | 0.0675 | 0.0496 |



(a)



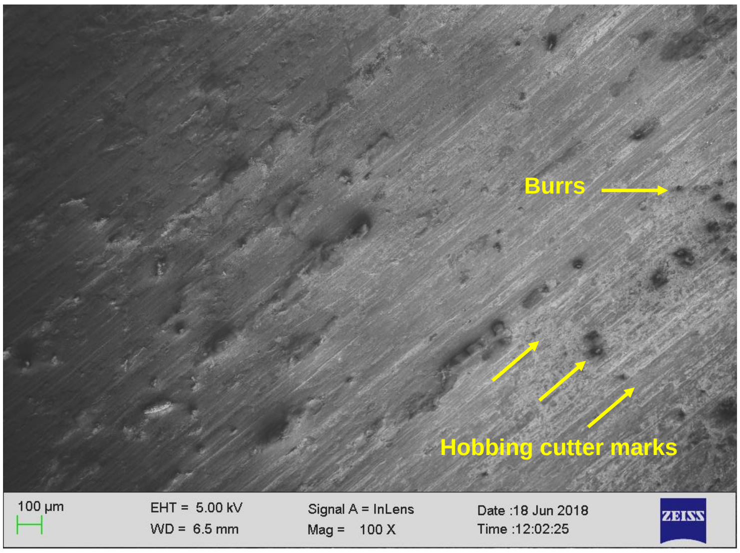

(b)

**Figure 4.9:** Variation of (a) coefficient of friction; and (b) friction force with time during reciprocating fretting test of flank surface of the hobbed spur gear before finishing, best finished hobbed spur gear by AFF process and best finished laser lay profile hobbed spur gear by AFF process.

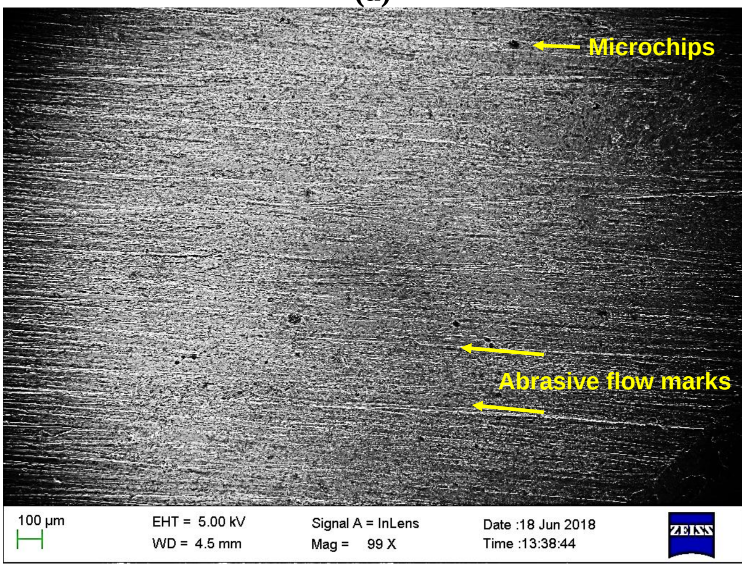
It is clear from Table 4.5 and Fig. 4.9 that values are significantly decreased after finishing by AFF process of hobbed spur gear and laser lay profile hobbed spur gear. The values of coefficient of friction decreased from 0.683 (hobbed spur gear before finishing) to 0.497 (for best finished hobbed spur gear) and 0.379 (for best finished laser lay profile hobbed spur gear); frictional force decreased from 33.48 to 24.35 (for best finished hobbed spur gear) and 18.64 (for best finished laser lay profile hobbed spur gear); specific wear rate decreased from 14.8 x $10^{-6}$ to 5.73 x $10^{-6}$ (for best finished hobbed spur gear) and 4.22 x $10^{-6}$ $mm^3$/N-m (for best finished laser lay profile hobbed spur gear); wear rate from 7.27 x $10^{-4}$ to 2.81 x $10^{-4}$ (for best finished hobbed spur gear) and 2.67 x $10^{-4}$ (for best finished laser lay profile hobbed spur gear) $mm^3$/m; and sliding wear volume from 0.174 to 0.067 (for best finished hobbed spur gear) and 0.049 (for best finished laser lay profile hobbed spur gear) $mm^3$ of its flank surfaces. High improvement in wear resistance of laser lay profile hobbed spur gear observed compared to hobbed spur gear because of more improvement in surface roughness.

## 4.6 Analysis of Surface Quality of Gear by SEM

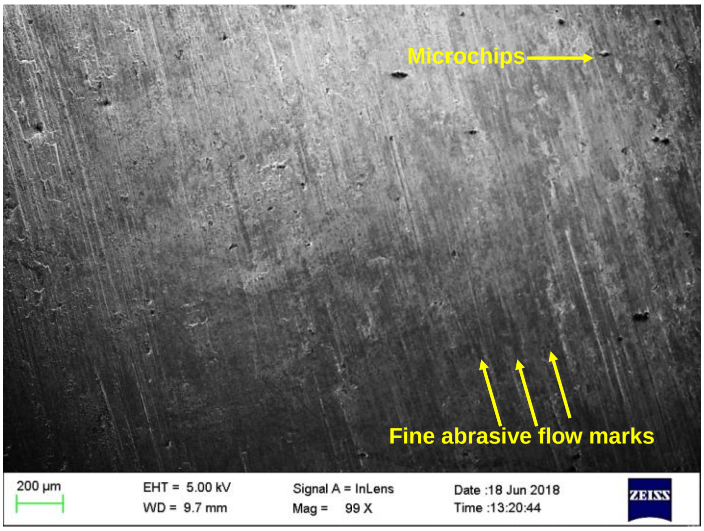
Figure 4.10 shows SEM micrograph of the gear flank surfaces of (a) unfinished hobbed spur gear, (b) best finished hobbed spur gear by AFF and (C) best finished laser lay profile hobbed spur gear by AFF. The surface of unfinished hobbed spur gear contain tool marks, microchips, burrs, cracks caused by hobbing cutter (Fig4.10 a). AFF removed cutter marks burrs, pits present on flank surface of hobbed spur gear completely and produced smooth surface (Fig.4.10 b). In laser lay profile hobbed spur gear finished by AFF (Fig.4.10 c) abrasive marks are very less visible and very smooth surface compared to hobbed spur gear finished by AFF (Fig.4.10 b). The abrasive marks on finishing surface clearly visible and some piled up material present in both hobbed spur gear and laser lay profile hobbed spur gear finished by AFF, which indicates micro cutting and micro ploughing mode of material removal followed by abrading action.




**(a)**




**(b)**




**(c)**

**Figure 4.10:** SEM micrograph of the gear flank surfaces of (a) unfinished hobbed spur gear, (b) best finished hobbed spur gear by AFF process and (C) best finished laser lay profile hobbed spur gear by AFF process.

# Chapter 5

## Conclusions and Future Scope

This chapter presents the conclusions based on the measured values of surface roughness, microgeometry, microhardness and wear test of spur gears for different processing conditions.

### 5.1 Conclusions

- Laser power and number of passes play significant role in generating laser lay profile on gear flank surface. Combination of 20 W laser power and 5 number of passes have been found to be optimum parametric combination for fabrication of fine lay profile on gear flank surface.
- Percentage improvement in microgeometry and surface roughness parameters of the AFF-finished hobbed spur gears increases (i.e. microgeometry and surface finish improve) with finishing time. The rate of increment is less at the early stage of finishing process. This is due to the presence of hobbing cutter marks causing higher peaks on flank surfaces of the spur gears. AFF medium reduces height of these peaks during early stage of finishing and subsequently AFF medium finishes all surface peaks equally, hence more improvements are observed.
- Percentage improvement in microgeometry and surface roughness parameters of laser lay profile spur gear finished by AFF is more than the spur gears directly finished by AFF due to a mesh like structure formed by creating homothetic laser texture normal to existing hobbed cutter marks, which deflect flow direction of abrasive. As a result, the abrasive now has to travel more distance resulting in higher material removal rate.
- Microhardness improvement for laser lay profile hobbed spur gear finished by AFF is more due to continuous impact of abrasive particle because of high extrusion pressure of AFF and compressive residual stresses due to laser lay profiling. The combined effect of AFF action and LT impingement causes increase of residual stress and simultaneously improvement in fatigue strength.
- AFF process does not give any undesirable effects during gear finishing as compared to conventional finishing process such as grinding burns in gear grinding, microgeometry deviations due to longer lapping cycles in gear lapping.

- Laser lay profiling is an effective method to improve surface finish and MRR in AFF process. It improves wear resistance and microhardness by inducing compressive residual stress without any thermal damage to flank surface. It is not required to make any changes in existing AFF apparatus and fixture unlike other hybrid variants of AFF process. It is quick, economical and effective method to increase productivity of AFF process.

## 5.2 Scope for the Future Work

Since, present work was very first attempt to investigate the effect of homothetic laser lay profile on the microgeometry and surface quality of hobbed spur gear, therefore it may have certain limitations. Following is scope for future work:

- Effect of homothetic laser lay profile on the microgeometry and surface quality can be investigated on helical, bevel gears etc.
- Effect of different laser lay profile (i.e. wavy, inclined, micro-spot etc.) can be investigated on microgeometry and surface quality of different gears.
- Comparison of noise and vibration level of laser lay profile hobbed spur gear finished by AFF and hobbed spur gear directly finished by AFF.
- Developing relationship between microgeometry and laser lay profile to analyze noise and vibrations levels in spur gears.

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