Investigations on Surface Quality of Helical Gears Finished by Pulsed Electrochemical Honing

M.Tech. Thesis

By

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Discipline of Mechanical Engineering

Indian Institute of Technology Indore

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Investigations on Surface Quality of Helical Gears Finished by Pulsed Electrochemical Honing

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

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Candidate's Declaration

I hereby certify that the work which is being presented in the thesis entitled **"Investigations on Surface Quality of Helical Gears Finished by Pulsed Electrochemical Honing"** in the 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** 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 2015 to June 2016)** under the supervision of **Prof. 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.

(Pravin Rai)

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)**

Pravin Rai has successfully completed his M.Tech Oral Examination held on **……….**

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Signature of Convener, DPGC
Date:

Signature of PSPC Member 1
Date:

Signature of PSPC Member 2
Date:

Signature of Chairman, Oral Examination Board with date

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Last, but not least, I would like to dedicate this thesis to **my parents**, **sisters** and **my friends**, for their love, patience, and understanding, because without their support, I would have never reached where I am today.

(Pravin Rai)

Dedicated

to

My Family

Abstract

Improvement in surface quality of helical gears is required to enhance their service life, operating performance and mechanical efficiency, and to reduce noise and transmission errors. Pulsed-electrochemical honing (PECH) is a fine finishing process hybridizing pulsed-electrochemical finishing (PECF) and mechanical honing. This work reports on improving the surface quality of $20MnCr_5$ alloy steel helical gears in terms of surface finish and micro-geometry by studying effects of pulse-on time, pulse-off time, finishing time and voltage on them. The experiments were conducted using Taguchi L_{16} experimental design by varying the each input parameter at four levels. The results have shown improvements in the surface quality of the PECH-finished helical gears. Pulse-on time of 6 ms, pulse-off time of 3 ms, finishing time of 8 minutes and voltage of 16 V produced the best surface quality gear. The improvements in micro-geometry of helical gears in terms of average percentage improvement in total profile error, total lead error, cumulative pitch error, and in total runout were found as 41.3%, -23.2%, 74.7%, and 47.8%, respectively and the improvements in surface roughness of helical gears in terms of average percentage improvement in average surface roughness, maximum surface roughness and depth of surface roughness were found as 41.6%, 32.3% and 39.6%. This work proves capability of PECH for fine-finishing the helical gear flank surfaces simultaneously improving its micro-geometry and surface finish.

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Nomenclature

F_p	Cumulative pitch error (μm)
f_p	Single pitch error (μm)
F_r	Total runout (μm)
f_u	Adjacent pitch error (μm)
F	Faraday's constant
I	Amount of current passed in the IEG (A)
J	Current density in the IEG (A/mm^2)
K	Wear coefficient
k	Factor that indicated proportion of the total thickness of material removed from the valleys in one cycle of PECF and mechanical honing
K_e	Electrical conductivity of the electrolyte (Ω^{-1}mm^{-1})
N_s	Number of revolution of the workpiece gear per second (rps)
r	Radius of the involute arc (mm)
R_a	Average surface roughness (μm)
r_b	Radius of the base circle (mm)
R_{max}	Maximum surface roughness (μm)
R_z	Depth of surface roughness (μm)
R_{zi}	Depth of surface roughness of an unfinished gear tooth (μm)
R_{zPECF1}	Depth of surface roughness after one cycle of PECF (μm)
t	Finishing time (sec)
T	Total number of teeth of the workpiece gear
V	Applied voltage (Volts)
ΔV	Total voltage drop in the IEG (volts)
V_{PECH}	Volumetric material removal rate in PECH (mm^3/s)
V_{PECF}	Volumetric material removal rate in PECF (mm^3/s)
V_h	Volumetric material removal rate due to mechanical honing (mm^3/s)
Y	Inter-electrode gap (mm)
μ	Coefficient of sliding friction
η	Current efficiency
α	Pressure angle of the involute profile (deg)
δ	Duty cycle (%)
λ	Percentage of pulse-on time to attain set value of the applied voltage (%)
ρ_W	Density of the workpiece gear material (g/mm^3)
θ	Angle subtended by the involute at its centre (deg)

Abbreviations

AMP	Advanced Machining Processes
CNC	Computer Numeral Control
DC	Direct Current
DOE	Design of Experiments
DOF	Degree of Freedom
ECD	Electrochemical Dissolution
ECM	Electrochemical Machining
ECF	Electrochemical Finishing
ECH	Electrochemical Honing
FC-ECH	Filed Control Electrochemical Honing
HMP	Hybrid Machining Processes
IEG	Inter Electrode Gap
MRR	Material Removal Rate
PECF	Pulse Electrochemical Finishing
PECH	Pulse Electrochemical Honing
PECMP	Pulse Electrochemical Mechanical Polishing
PIf_p	Percentage Improvement in Single Pitch Error
PIf_u	Percentage Improvement in Adjacent Pitch Error
PIF_p	Percentage Improvement in Cumulative Pitch Error
PIF_r	Percentage Improvement in Runout
PIR_a	Percentage Improvement in Average Surface Roughness
PIR_{max}	Percentage Improvement in Maximum Surface Roughness
PIR_z	Percentage Improvement in Depth of Surface Roughness
SSFC-ECH	Slow Scanning Filed Control Electrochemical Honing

Organization of the Thesis

This thesis is organized into six chapters with following contents:

Chapter 1 presents introduction of gear, applications of gears, gear manufacturing process, gear finishing process, ECH and PECH processes, gear micro-geometry and surface finish.

Chapter 2 presents review of past work on ECH of gear, research gaps identified based on this review and the research objectives defined based on the identified research gaps.

Chapter 3 presents fabrication of finishing chamber and subsystems of the Experimental setup.

Chapter 4 describes planning and details of experiments carried out for the present work. It also presents the experimental procedure.

Chapter 5 presents experimental results and their analysis focusing on the effects of variable input parameters of PECH process on workpiece gear along with identification of optimum level of the process parameters.

Chapter 6 highlights the conclusions derived from the present work and scope for future work based on the limitations of the present work.

Chapter 1

Introduction

Gears are machine elements that transmit motion and power mechanically and positively (i.e., without slip) with and without change in the direction and 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 high. Generally gears can be classified either according to configuration: external and internal gears; or according to arrangement of axes of engaging gears namely:

- ❖ **For transmission between parallel shafts:** straight toothed spur gear, single helical and double helical or Herringbone gears
- ❖ **For transmission between intersecting shafts:** bevel gears (straight-tooth, spiral-tooth, zero-bevel, crown, and mitre type)
- ❖ **For transmission between non-parallel and non-intersecting shafts:** spiral gears, hypoid gears, worm and worm wheel.

Gears have vast application areas due to their unique contribution to operation of many machines, equipment and devices. Some worth-mentioning application areas of gears include: automotive, aerospace, marine, machine tools, other modes of transportation, control systems, large mills used for producing cement, iron ore, rubber and roll steel, toys, office equipment, home appliance, etc. It is very difficult to estimate exactly the total market volume, but annually at least 2–3 billion gears are consumed worldwide with turnover running into several billion euros. Despite of excellent market position, following are the increasing requirements for further improvement of gear drives as mentioned by **Goch (2006)**:

- ❖ Improvement of power density and transmitted power
- ❖ Reduction in running noise, toxic emissions and price
- ❖ Increase in reliability and service life time
- ❖ Easy disposal and material recycling of the used gears
- ❖ Integration of electronic systems such as data acquisition, logical control, integrated safety system, etc.

1.1 Gear Manufacturing

The gear tooth flanks have a complex and precise shape with requirements of high surface quality and surface integrity. Special attention is paid to gear manufacturing because of the specific requirements of the gears. Gears can be manufactured by casting, forging, extrusion, powder metallurgy, machining. Table 1 mentions different gear manufacturing methods. The initial operations that produce a semi-finished part which is used as raw or starting material in manufacturing a gear is called blanking operation and part is called a gear blank.

Table 1.1: Different types of gear manufacturing processes **(Jain and Petare, 2016)**

Gear manufacturing processes Conventional gear manufacturing processes		Special and advanced gear manufacturing processes
Generative type	Non-generative type	
1. Hobbing 2. Shaping 3. Milling 4. Broaching 5. Bevel gear generating	1. Casting 2. Powder metallurgy 3. Forming • Stamping • Extrusion • Forging • Hot Embossing	1. Gleason method 2. Template gear cutting 3. EDM and micro-EDM (m-EDM) 4. WEDM and micro-WEDM (m-WEDM)

Usually, machining is the most commonly used to achieve the final size, shape and surface finish of a gear. Two principal methods of gear machining are: (i) gear forming; and (ii) gear generation. Following sections describes them briefly

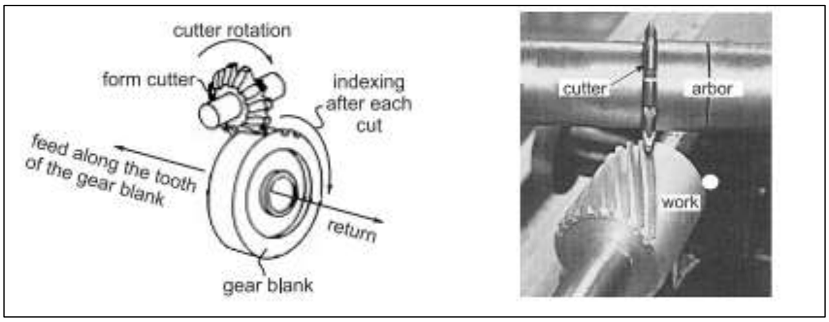
1.1.1 Gear Forming

In gear forming, the cutting tool has a shape complementary to spacing between two gear teeth as shown in Fig.1.1. Form milling and broaching are two methods of gear forming.

Fig. 1.1: Principle of gear forming.

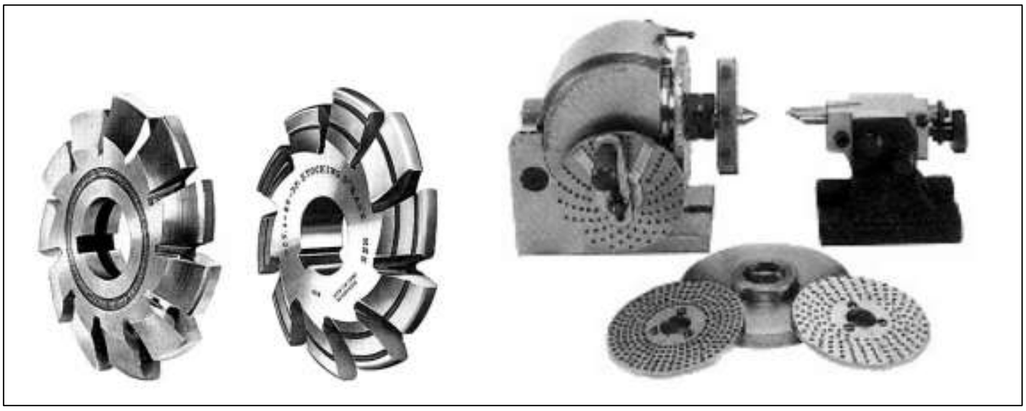
1.1.1.1 Form Milling

In form milling, a form cutter travels axially along the width of the gear blank to an appropriate depth to produce the gear teeth as shown in Fig 1.2. After each tooth is cut, the form cutter is withdrawn and the gear blank is indexed for cutting next tooth using an indexing mechanism. The process continues until all teeth are cut. Each cutter is designed to cut a range of gear tooth. Different form cutters are used for rough and finish cut as depicted in Fig 1.3(a) Precision of the form-cut tooth profile depends on the accuracy of the cutter and the machine and its stiffness. Indexing is the process of evenly dividing the circumference of a gear blank into equally spaced divisions. The index head of the indexing fixture is used for this purpose. The index fixture consists of an index head (also dividing head, gear cutting attachment) and footstock as shown in Fig 1.3(b) which is similar to the tailstock of a lathe. The index head and footstock are attached to the worktable of the milling machine. An index plate containing graduations is used to control the rotation of the index head spindle. Gear blanks are held between centers by the index head spindle and footstock. Workpiece may also be held in a chuck mounted to the index head spindle or may be fitted directly into the taper spindle recess of some indexing fixtures.



(a) (b)

Fig. 1.2: Cutting gear teeth by form milling (a) working principle; and (b) form milling of a helical gear.



(a) (b)

Fig. 1.3: (a) Form cutters used in form milling for finish cut (left) and rough cut (right); (b) dividing head (Left), and footstock (Right) used to index the gear blank in form milling.

1.1.1.2 Broaching

Broaching is used to cut gear teeth and is particularly suitable for cutting teeth of internal gears. The process is fast and produces fine surface finish with high dimensional accuracy. Broaches are expensive and a separate broach is required for each size of gear. Therefore, this process is suitable mainly for high-quantity production of gears. Broach moves along the width of the gear blank to cut teeth as shown in Fig.1.4.

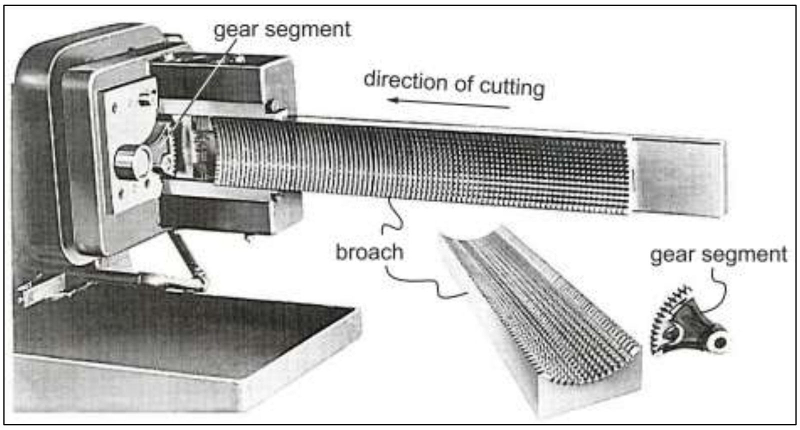


Fig. 1.4: Producing teeth on a gear segment by horizontal external broaching.

1.1.2 Gear Generation

In the gear generation process, gear tooth are generated as an outline of the subsequent positions of the gear cutter which resembles in shape to a mating gear of a gear pair. Fig. 1.5 shows various stages in generating one tooth of a gear by gear shaping process. Cutters and blanks rotate in a timed relationship and a proportional feed rate is maintained between them. Gear generating is used for high production runs and for finishing cuts.

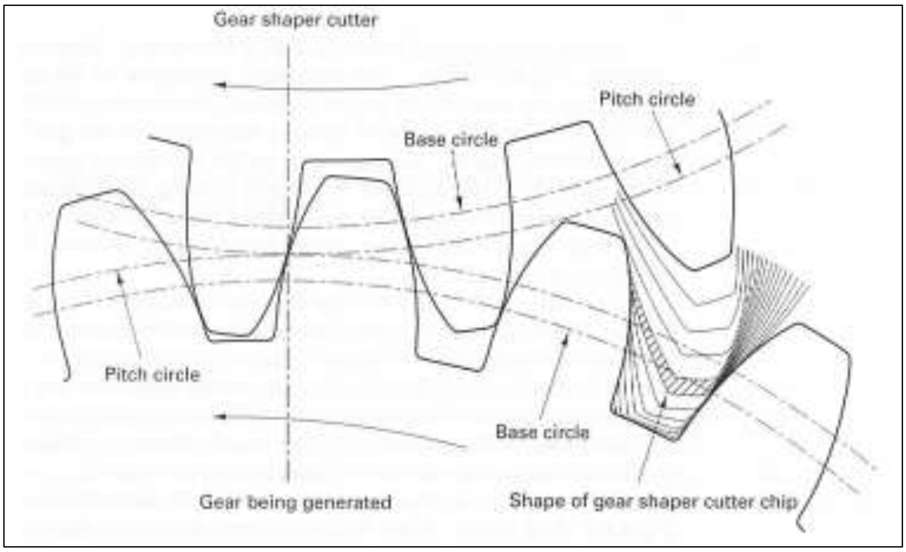


Fig. 1.5: Generating action of a cutter in gear shaping process.

Milling and shaping are two machining processes used for gear generation. There are several modifications of these processes for different cutting tool used,

- ❖ Gear Hobbing or gear milling with a hob
- ❖ Gear shaping using a pinion-shaped cutter
- ❖ Gear shaping using a rack-shaped cutter

1.1.2.1 Gear Hobbing

Gear hobbing 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.1.6 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.

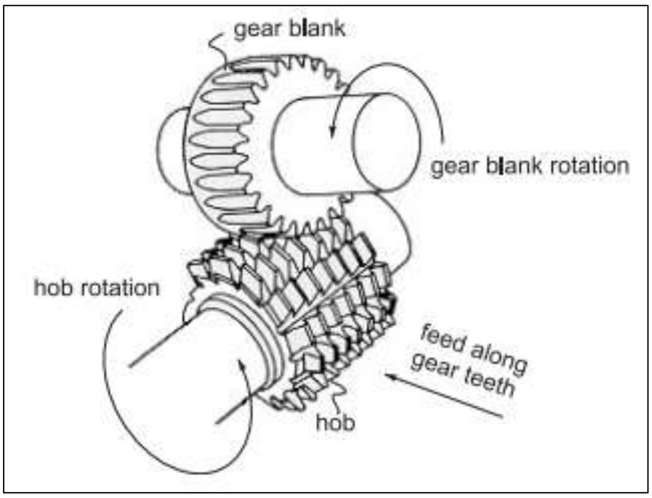


Fig. 1.6: Principle of cutting teeth by hobbing operation.

1.1.2.2 Shaping with a Pinion Shaped Cutter

This is a modification of the gear shaping process in which gear teeth are generated by meshing the gear blank with a rotating and reciprocating pinion-shaped cutter as shown in Fig.1.7. The cutter has its axis parallel to the axis of the gear to be cut.

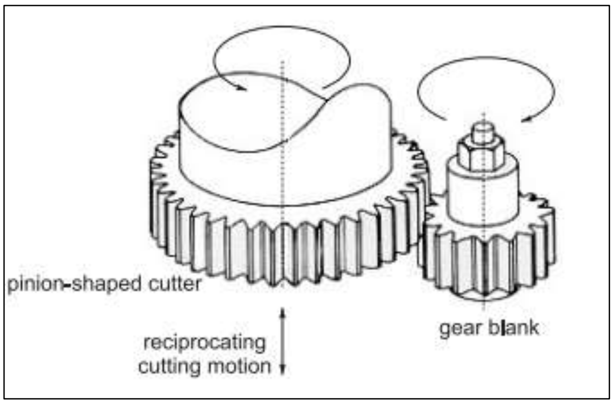


Fig. 1.7: Principle of gear generation by gear shaping operation with a pinion-shaped cutter.

1.1.2.3 Shaping with a Rack Shaped Cutter

In this process, gear teeth are generated on gear blank using a rack-shaped cutter which reciprocates slowly parallel to the axis of the rotating gear blank as shown in Fig.1.8. The cutter is disengaged at suitable intervals and returned to the starting point whereas gear blank keeps on rotating.

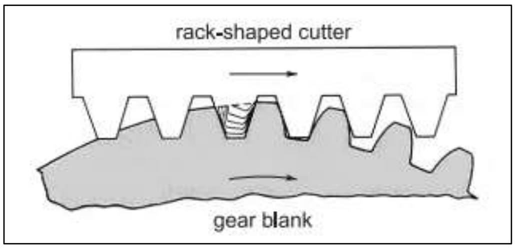


Fig. 1.8: Principle of gear generation by gear shaping operation using a rack-shaped cutter.

1.2 Gear Finishing

Gears manufactured by any process do not possess the desired surface finish, micro-geometry, dimensional accuracy and properties necessitating use of combinations of different finishing and property enhancing processes which may be conventional or advanced or their combination. Conventional gear finishing are shaving, grinding, honing, and lapping. Following sections describe them briefly.

1.2.1 Gear Shaving

Gear shaving is a chip forming finishing operation that removes small amounts of material from the working surfaces of gear teeth. Serrated helical cutter gear as shown in Fig 1.9 and the workpiece gear are rotated in close mesh edges of cutter shaves producing fine hair like chips. The axis of cutter and work gear are crossed at a predetermined angle during the shaving operation.

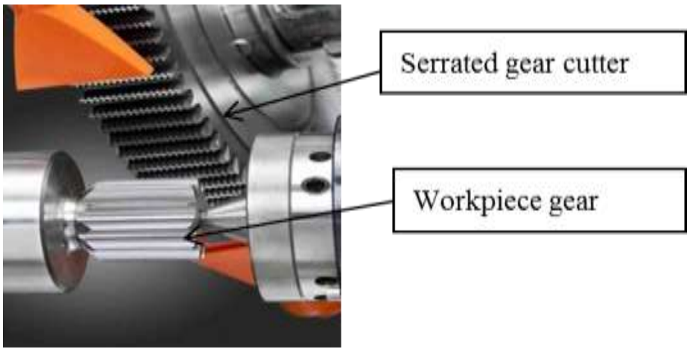
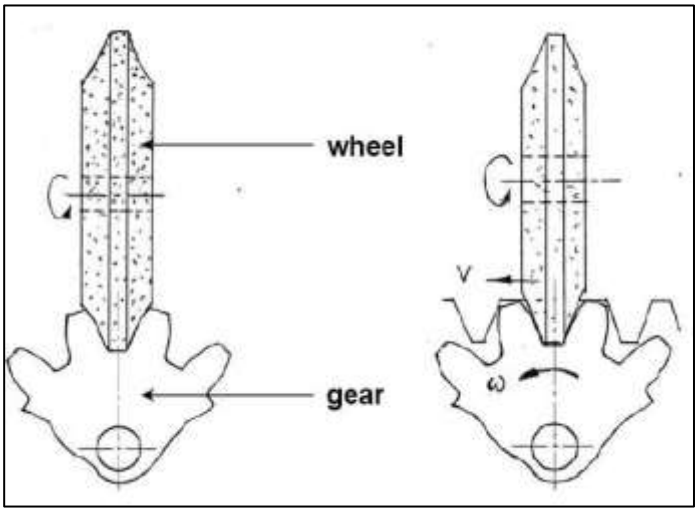


Fig. 1.9: Working principle of gear shaving process.

1.2.2 Gear Grinding

Gear grinding is an effective means of finishing gears made of heat-treated high-hardness steels (40 HRC and above) using a properly formed and dressed grinding wheel which finishes the gear teeth flanks by fine abrading action of the abrasives. There are two types of gear grinding: form grinding or generative gear grinding.

- In form grinding, the grinding wheel is dressed to the form that is exactly required on the gear as shown in Fig 1.10(a). Need of indexing makes this process slow and less accurate. The wheel or dressing has to be changed with change in module, pressure angle and even number of teeth. Form grinding may be used for finishing straight or single helical spur gears, straight toothed bevel gears, worm and worm wheels.
- Generative gear grinding [Fig 1.10(b)] is the simplest and most widely used method and is very similar to spur gear teeth generation by one or multi-toothed rack cutter.



(a) (b)

Fig. 1.10: Gear teeth finishing by (a) form grinding, (b) generative type grinding using single tooth cutter.

1.2.3 Gear Honing

Gear honing is a particularly effective method of removing nicks and burrs from the active profiles of teeth of a heat treated gear. It is a hard-gear-finishing method, which was developed to improve the noise characteristics of the hardened gears. It uses an abrasive-impregnated plastic helical gear-shaped tool which is run in mesh with the hardened gear in crossed-axes relationship as shown in Fig 1.11. The workpiece gear is driven by the honing tool at high speeds while being traversed back and forth across the honing tool in a path parallel to axis of the workpiece gear. The workpiece gear is rotated in both directions during the honing cycle.

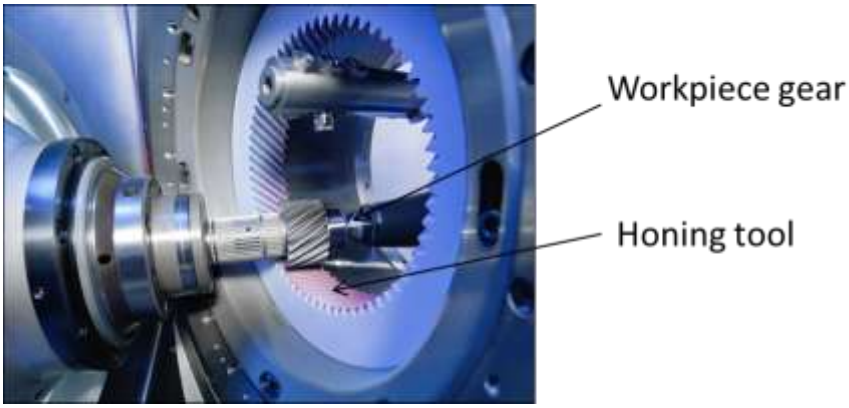


Fig. 1.11: Working principle of gear honing.

1.2.4 Gear Lapping

Gear lapping is a low-speed and low-pressure abrading operation used to refine the tooth surface and to reduce noise levels of a pair of gears. The gear pair is run under a controlled light load while a suitable lap compound, which is mixture of an abrasive and carrier fluid, is pumped over the gear pair as shown in Fig 1.12. Similar to gear grinding and honing, lapping can also be used for heat treated gears.

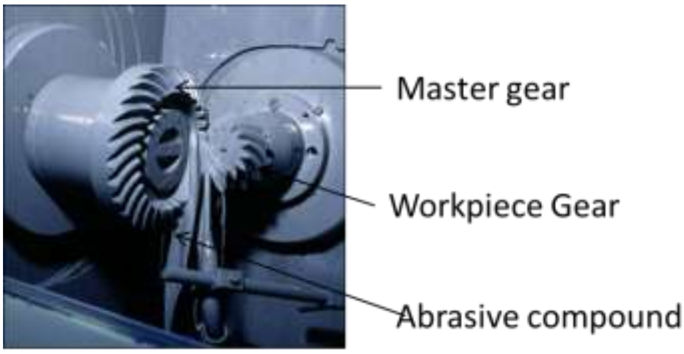


Fig. 1.12: Working principle of gear lapping.

1.2.5 Gear Burnishing

In this process, the machined unhardened gear is rolled under pressure with three hardened master gears of high accuracy and finish as shown in Fig 1.13. The minute irregularities of the machined gear teeth are smeared off by cold plastic flow, which also helps in improving the surface integrity of the desired teeth.

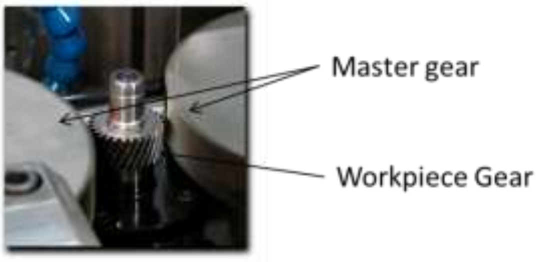


Fig.1.13: Working principle of gear burnishing.

The conventional gear finishing processes such as gear grinding, gear shaving, gear honing, gear lapping are costly, have low productivity and limitation on gear material hardness, etc. Table 1.1 summarizes their own applicability and limitations. This necessitates the exploration of advanced gear finishing processes such as electrochemical honing (ECH).

Table 1.2: Summary of conventional finishing processes of the gears.

Gear finishing processes	**Applicability**	**Limitations**
Gear shaving	Widely used for teeth of straight or helical toothed external spur gears and worm wheels of moderate size.	Only for gears either having hardness up to 40 Rockwell C scale or unhardened.
Gear grinding	Frequently used to finish tooth profiles of different types of gears of hard material that has been heat-treated to a high hardness level after gear cutting	Relatively very expensive and complicated. Form grinding is very time-consuming
Gear lapping	Normally used for spur, helical, bevel, spiral bevel, and hypoid gears. Usually employed on those gears that have been shaved and hardened.	Only corrects minute deviations from the desired gear tooth profiles. Longer lapping cycles may affect accuracy of the involute profile in a detrimental manner.
Gear honing	Can be used for hardened gears.	Limited life of honing gear tool.
Gear burnishing	Used for helical gears.	Can be used for unhardened gears only. It is localized cold-working operation, some undesirable effects such as localized surface stresses and non-uniform surface characteristics.

1.3 Introduction to ECH and PECH

ECH is a hybrid super finishing process which combines capabilities and advantages of electrochemical machining (ECM) with mechanical honing and simultaneously overcoming their individual limitations. Main capabilities of ECM process include: capability to machine/finish material of any hardness, production of stress-free and crack-free surface, higher MRR and no tool wear. While, main capabilities of honing are: ability to correct the geometric errors and controlled generation of functional surfaces. Main limitation of ECM process is passivation of anodic workpiece surface by the metal oxides formed due to evolution of oxygen gas at anode during its electrolytic dissolution. This anode passivation prohibits further electrolytic dissolution of the workpiece. While, major limitations of honing process includes limited life of honing tool, low productivity, incapability of finishing a hardened workpiece and possibility of mechanical damage (i.e. micro-cracks, hardness alternation and plastic deformation) to the workpiece material. This makes ECH as an ideal choice to explore as an alternative, superior and economical process for gear finishing.

ECH is a hybrid micro-finishing process combining advantages of ECM and honing in a single process and overcoming their limitations at the same time. ECH is one of the most potential hybrid machining processes combining the faster material removal capability of electrochemical machining (ECM) and capability of correcting shape-related errors of conventional honing. Moreover, pulse assistance in ECH (PECH) provides the relaxation period to the system during off time to discharge the dregs out of the electrodes' gap and improves the process capability.

1.3.1 Process Principle of ECH for Finishing of Gears

The actual working principle of ECH of gears is explained by **Chen *et al.* 1981** with the help of schematic of finishing chamber arrangements as depicted in Fig1.14 in which the workpiece gear '1' is clamped between centers of the work table, which is reciprocating axially as indicated by the arrowhead '3'. The cathode in the ECM process should be electrically conductive to produce electrolysis action, but in ECH of gears, the cathode gear is in constant mesh with workpiece gear, which will cause a short circuit during the process. Therefore to avoid the short circuiting, the cathode gear consists of a gear '7' made of a conducting material sandwiched between two insulating gears '6'. There is difference of 'δ' (i.e. IEG) between the gear profiles of the conducting gear and insulating gears. The cathode has the same involute profile as the workpiece. The axis of the shaft on which the cathode is mounted is parallel to the axis of workpiece gear. A full stream of electrolyte is supplied to the gap 'δ', and a DC current is passed through the gap. During the process of material removal from the tooth flank, the electrolyte forms a metal oxide protective film on the workpiece gear tooth surface which protects the surface from being further removed. This oxide layer on the tooth surface of the workpiece gear is scraped by the honing gear when it comes in contact with a cross-axis arranged honing gear '2'.

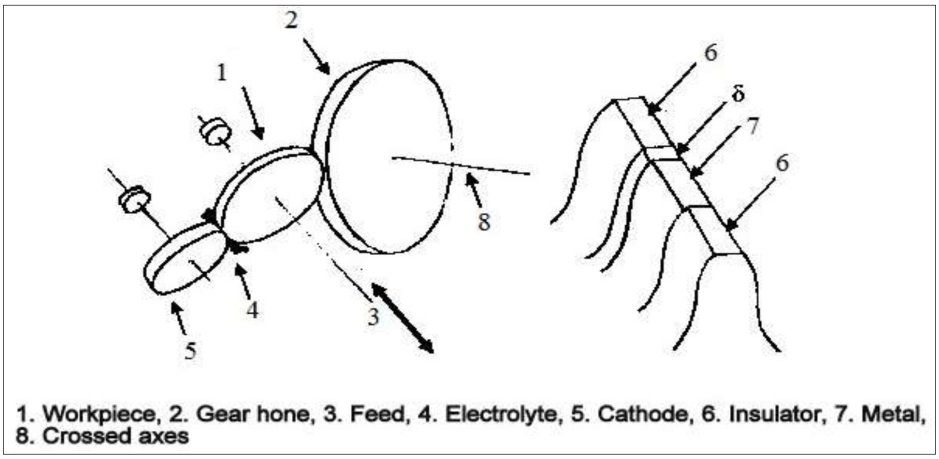


Fig. 1.14: Design of cathode tool and working principle of ECH of gears (**Chen *et al.*1981**).

Following important advantages of ECH make it superior to conventional finishing processes:

- ❖ Theoretically, there is no tool wear because there is no physical contact between anode (i.e. workpiece gear) and cathode (cathode gears) tool.
- ❖ Finishing of the workpiece gear is independent of their material mechanical properties i.e. hardness, brittleness, strength, ductility.
- ❖ Uniformity of material removal can be achieved as the material removal is due to its anodic dissolution.
- ❖ Ability to produce stress-free surfaces and crack-free smooth surfaces.

1.4 Micro-geometry of Gears

Micro-geometry of a gear is evaluated in terms of form error and location error. **Gupta and Jain (2014)** have mentioned that higher values of form error and location error in a gear lower its load carrying capacity and increase noise and errors in motion transfer during its use. Following sections briefly describe the concept of form error and location error.

1.4.1 Form Error

Profile error and lead error are two components of form error. Each is described in below sections.

1.4.1.1 Profile Error

Profile form error ($f_{f\alpha}$) is difference between the nominal or theoretical form and actual or measured form of an involute profile [Fig. 1.15(a)]. *Profile angle error* ($f_{H\alpha}$) is difference between the nominal angle and actual angle of an involute profile [Fig. 1.15(b)]. *Total profile error* (F_α) defines the form and location of the involute profile of a gear. Total profile error significantly affects noise generation characteristics of a gear. It is sum of profile form error and profile angle error [Fig. 1.15(c)].

(a) (b) (c)

Fig. 1.15: Concept of (a) profile form error ($f_{f\alpha}$); (b) profile angle error ($f_{H\alpha}$); and (c) total profile error (F_{α}).

1.4.1.2 Lead Error

Lead form error ($f_{f\beta}$) is difference between the nominal lead form and actual lead form [Fig. 1.16(a)]. *Lead angle error* ($f_{H\beta}$) is the difference between nominal helix angle and actual helix angle [Fig. 1.16(b)]. It is also known as lead parallelism or helix slope deviation or tooth alignment error or flank line angle error. *Total lead error* or *total alignment error* (F_{β}) of a gear defines form and location of its tooth flank. It is the most influencing factor in determining load carrying capacity of a gear. It is sum of lead form error and lead angle error [Fig. 1.16(c)].

(a) (b) (c)

Fig. 1.16: Concept of (a) lead form error ($f_{f\beta}$); (b) lead angle error ($f_{H\beta}$); and (c) total lead error (F_{β}) .

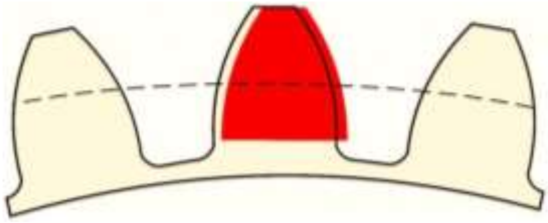
1.4.2 Location Error

It consists of pitch error and runout of a gear. These errors significantly affect motion transfer characteristics and noise generation characteristics of a gear.

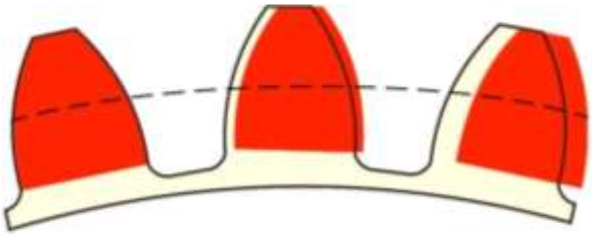
1.4.2.1 Pitch Error

Pitch error has three components: *Single pitch error* (f_p) is the difference between the actual and nominal angular positions of two respective flanks on the two consecutive gear teeth [Fig. 1.17(a)]. *Adjacent pitch error or pitch-to-pitch deviation* (f_u) is the maximum difference between the angular deviations of any two adjacent right flanks or left flanks.

Cumulative pitch error (F_p) *or index error* is the difference between the summation of the theoretical values of pitches and summation of the actual values of the pitches over all the teeth of a gear. It represents difference between the most positive pitch and the most negative pitch values (i.e. vertical distance between the highest and lowest points of the pitch variation curve) among all the teeth of a gear as shown in Fig. 1.17(b).



(a)



(b)

Fig. 1.17: Concept of (a) single pitch error; (b) cumulative pitch error

1.4.2.2 Runout

Runout (F_r) describes radial location of all the teeth of gear with respect to its pitch circle. It is maximum difference between the actual radial positions of all teeth measured with respect to their nominal radial position as shown in Fig. 1.18. It is evaluated along the pitch circle at middle point of the face width.

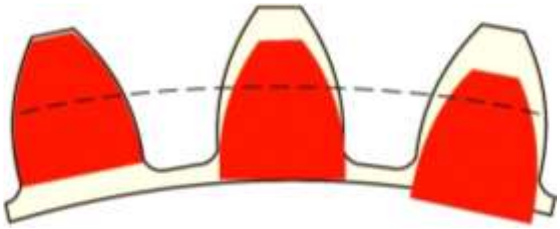


Fig. 1.18: Concept of runout.

1.5 Surface Roughness

Surface roughness often shortened to roughness, is a component of surface texture. It is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small, the surface is smooth. Roughness is typically considered to be the high-frequency, short-wavelength component of a measured surface. However, in practice it is often necessary to know both the amplitude and frequency to ensure that a surface is fit for a purpose. To overcome problems such as noise or repeatability, some roughness parameters are meant to be calculated on profile segments (or sampling lengths) and then averaged. Sampling length is usually defined as the cut-off length (λ_c) of the filter used to separate roughness and waviness. For example, using a cut-off length of 0.8 mm and 5 sampling lengths, parameters will be estimated on each segments and the parameter value will be given as the mean of these estimated values. Other parameters are defined and calculated on the evaluation length which usually is the profile length after filtering. **Average surface roughness (R_a)** is the arithmetic average of the absolute values of roughness profile ordinates as shown in Fig 1.19. **Maximum surface roughness (R_{max})** is the height between the deepest valley and the highest peak on the evaluation length. **Root mean square surface roughness (R_q)** corresponds to the standard deviation of the height distribution, defined on the sampling length. **Depth of surface roughness (R_z)** is the arithmetic mean of single roughness depths R_{zi} of consecutive sampling lengths. Single roughness depth (R_{zi}) is the vertical distance between highest peak and the deepest valley of the profile within a sampling length. **Maximum profile peak height (R_p)** is height of the highest peak from the mean line, defined on the sampling length. **Maximum profile valley depth** (**R_v**) is depth of the deepest valley from the mean line, defined on the sampling length.

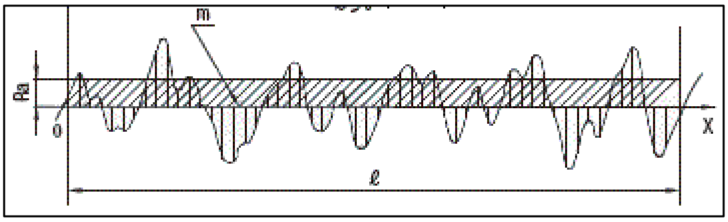


Fig. 1.19: Typical surface roughness profile.

Next Chapter presents review of the past works done in this field, identified research gaps, objectives and research methodology of the present work.

Chapter 2

Review of Past Work

Idea of electrochemical honing (ECH) was conceived during 1963-1965. Initially objective of this hybridization was to improve productivity of honing process using higher material removal rate (MRR) capability of ECF. Further, role of mechanical honing action was limited to remove the passivation layer of metal oxide to assist in continuation of material dissolution by ECF in addition its principle responsibility of generating the functional surface and improving geometrical accuracy. Despite the concept of ECH being originated in 1963 and having many unique capabilities, ECH remained in its infancy stage for very long time in many aspects due to lack of sustained research worldwide.

2.1 Past Work on Finishing of Gears by ECH and PECH

Limited works has been reported on finishing of gears by ECH and even less work has been reported on finishing the gears by PECH. **Jain *et al.* (2009)** have presented state-of-review of work done on finishing of internal cylinders and gears by ECH. Following paragraphs briefly summarizes the past work done using ECH and PECH for gear finishing:

Capello and Bertoglio (1979) used ECH for finishing the *hardened helical* gear. Their technological innovation consisted of removing material from tooth face of the anodic helical gear having involute profile, 17 teeth and module of 2.5, mating with a specially designed cathodic helical gear tool having with 64 teeth. The test bench was built to obtain reciprocating and rotary motion of the electrodes with a controlled inter-electrode gap. Their experimental results confirmed process feasibility and need for designing the electrode tools as a function of the electrochemical parameters. Though, their results also showed that the helix and involute profiles obtained were not acceptable but it just confirmed feasibility of using ECH for gear finishing.

Chen *et al.* (1981) used ECH for finishing of *spur* gears and reported improvement in their surface roughness and accuracy of tooth profile and reduction in noise level by 5-8 db. They concluded that (i) ECH of gears has fairly high ability to correct geometric errors and it is more productive than gear grinding; (ii) there is no cutting between honing and workpiece gear but only scrapping of protective oxide film formed on the anodic workpiece gear during ECF action; (iii) since honing speed is much lower than grinding, the problem of vibration and balancing is less critical; and (iv) ECH is favorable in finishing the hard and hardened materials. They also reported that the amount of the material removed and consequently accuracy of gear profile in ECH can be controlled either by controlling the amount of current passed in IEG or by controlling the finishing time.

Wei *et al.* (1987) attempted to improve the accuracy of *spur* gear profile by varying electric field intensity to control the electrolytic dissolution steplessly along the full profile of the gear using a newly developed gear-shaped cathode in process referred as field-controlled ECH (FC-ECH). Due to facility of adjusting the field intensity during the process of finishing, it becomes easier to improve the gear tooth profile along with tip or root relief. They reported that accuracy of the tooth profile can be greatly improved as the errors in the tooth profile of all the teeth are nearly same.

He *at al.* (2000) used time control method to correct *spur* gear tooth profile errors efficiently in a process which they referred as slow scanning field controlled ECH (SSFC-ECH). They also mentioned superiority of time control method over the current field control method. They used a gear shaped cathode which meshes with the workpiece gear during its finishing and which is exposed as cathode pole only on a strip on the tooth flank by varying centre distance between the cathode and workpiece gears slowly by a steeper motor. The electrolysis zone sweeps over the tooth flank from root to tip. An online profile error measuring device was provided. Computer computed the required discharging time which has relationship with dwelling time and sends the program to control material removal rate so as to cancel the error or to produce profile correction needed for silent gear transmission. A mathematical model was developed for calculating the required discharging time. Several ground gear with typical profile errors were subjected to trial machining on this working principle and results showed that it corrects the profile error very efficiently. This work further advances the concept of correcting the gear profile accuracy by ECH process.

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

Mishra *et al.* (2010) used ECH for finishing of *helical* gears made of EN8 and investigated the effects of applied voltage, electrolyte concentration and rotary speed of workpiece gear on percentage improvement in average and maximum surface roughness values using a mixture of 75% NaCl and 25% $NaNO_3$ as electrolyte. They reported that electrolyte concentration and applied voltage have more significant effects on ECH process performance compared to rotary speed. They found an optimum value of applied voltage as 27.6 volts, electrolyte concentration as 10% and rotary speed of workpiece gear as 68 rpm to obtain maximum percentage improvement of 94% and 86% respectively in average and maximum surface roughness values.

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

Shaikh *et al.* (2013) used ECH for finishing of straight bevel gears conceiving a novel idea of using twin complementary cathode gears and their an innovative arrangement with workpiece gear, honing gear in such a way that conical gears are finished without any requirement of providing reciprocating motion to the workpiece gear. **Shaikh and Jain (2014)** developed a mathematical model for surface roughness and MRR and reported voltage, electrolyte concentration, electrolyte temperature and electrolyte flow rate have significant influence on MRR and surface roughness. Same authors (**Shaikh and Jain, 2015)** observed considerable simultaneous improvements in geometrical accuracy and surface roughness and demonstrated that ECH can be highly productive alternative gear finishing process with finishing time as small as 2 minutes only.

Pathak *et al.* (2014) used PECH for finishing of straight bevel gears made of $20MnCr_5$ alloy steel and experimentally investigated the effects of PECH parameters and identified optimum parametric combination namely: pulse-on time as 2 ms, pulse-off time as 4.5 ms, finishing time as 6 minutes, electrolyte composition as 75 wt.% NaCl + 25 wt.% $NaNO_3$, electrolyte concentration as 7.5 wt. %, electrolyte flow rate as 20 lpm and rotary speed of the workpiece gear as 40 RPM to obtain simultaneous improvements in surface finish and micro-geometry parameters.

2.2 Identified Research Gaps

Following research gaps were identified based on the review of the past work done on gear finishing by ECH and PECH process:

- ❖ No work has been reported on the simultaneous improvement in micro-geometry, surface quality, wear characteristics and functional testing of the helical gears by ECH/PECH processes.
- ❖ Comparison of helical gears finished by PECH with gears finished by ECH.

2.3 Objectives of Present Work

Present research work was undertaken with main goal of quality finishing of helical gears using PECH process focusing on improving surface quality of helical gears in terms of micro-geometry, surface finish and finishing productivity.

2.4 Research Methodology

Figure 2.1 presents the research methodology used in the present work to meet the identified research objectives.

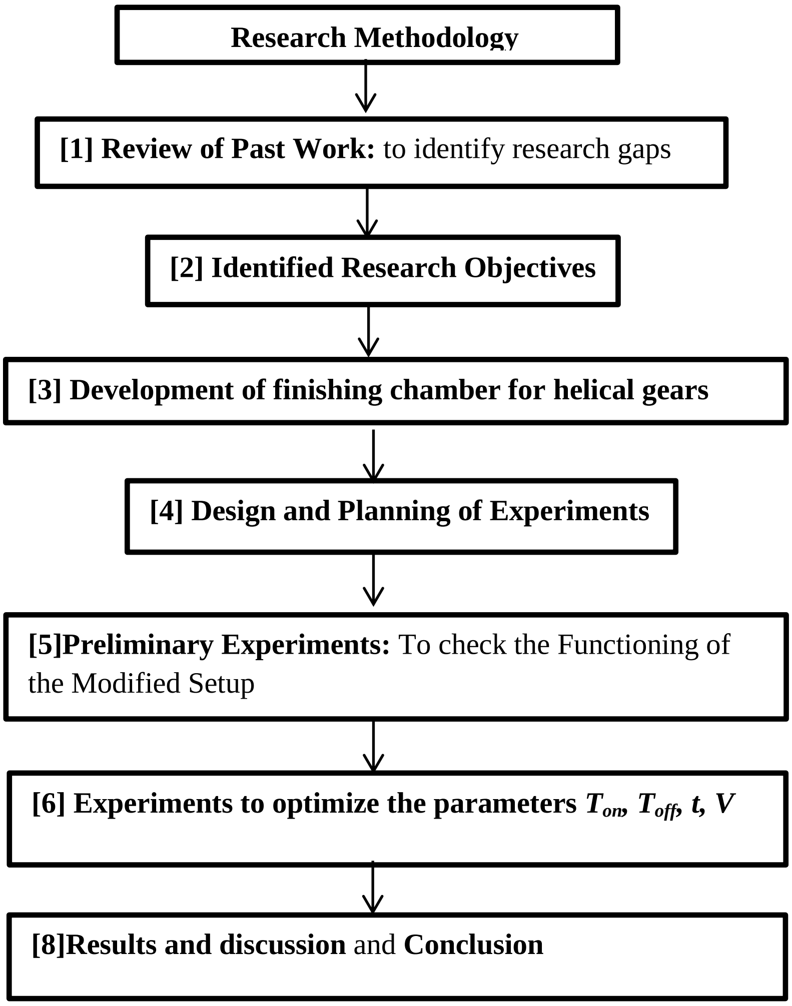


Fig.2.1: Research Methodology of the present work

Next Chapter presents in details of experimental apparatus developed for fine finishing of helical gears by PECH process.

Chapter 3

Development of Experimental Apparatus

3.1 Details of the Experimental Apparatus

An experimental apparatus for simultaneous improvement in micro-geometry, surface finish and finishing productivity of the helical gears was developed by incorporating following improvements in the experimental apparatus for ECH of helical gears described **Misra *et al.*** (2009):

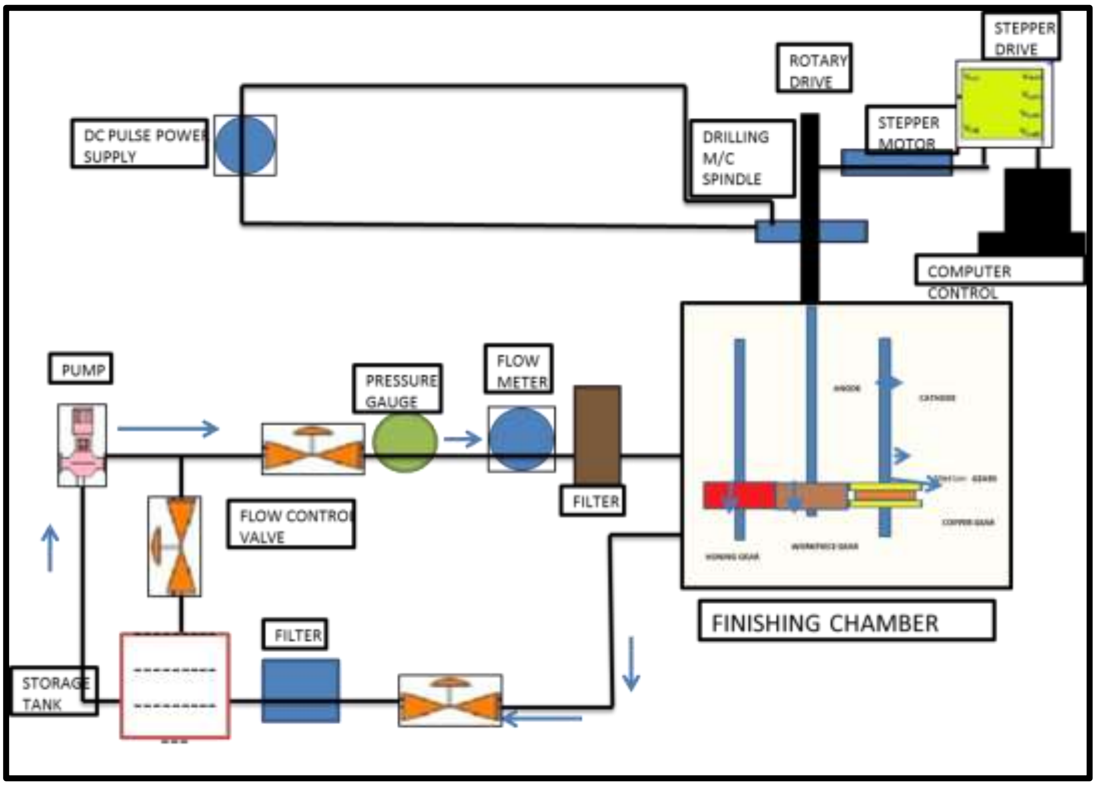
- ❖ In sandwich cathode gear, Metalon gears have been used instead of Bakelite gears which have high wear and erosion.
- ❖ Thrust bearings have been used instead of Teflon bolt to support vertical shaft to ensure smooth rotary motion to shafts.
- ❖ Redesign of the shafts holding workpiece, honing and cathode gears to reduce their size and weight. This will reduce runout and vibrations from the system.
- ❖ Use of programmable high current DC pulse power supply to ensure better finishing.

Figure 3.1(a) depicts the schematic diagram of the developed experimental apparatus while Fig. 3.1 (b) shows its program. The apparatus consists of following major subsystems:

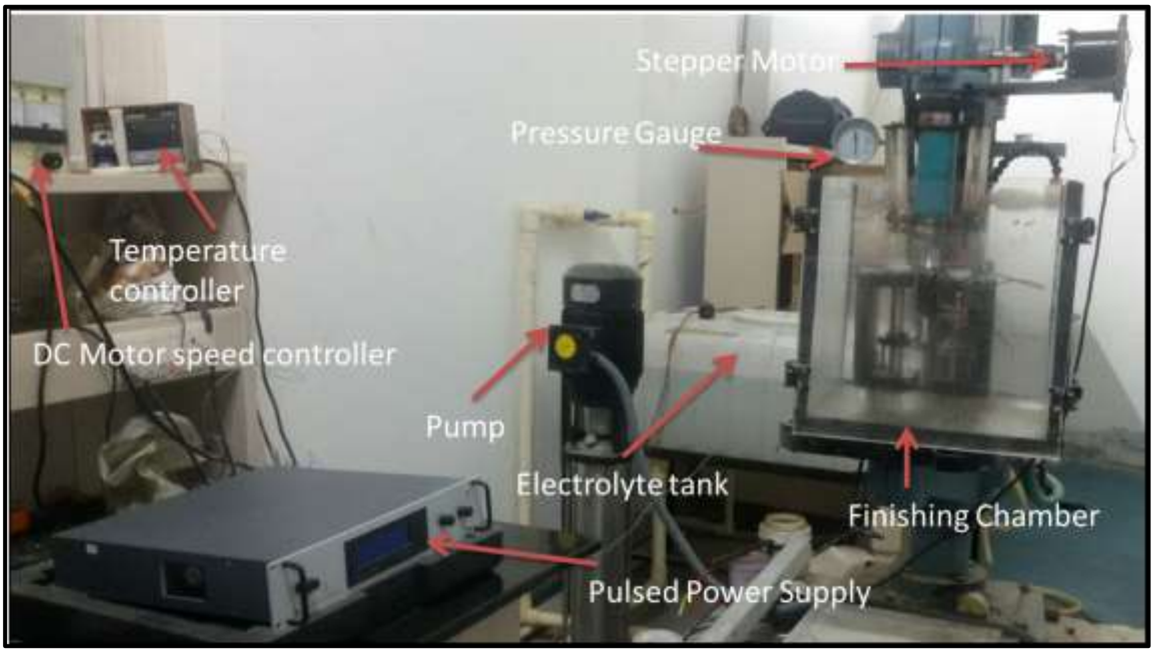
- ❖ Power supply system
- ❖ Electrolyte supply system
- ❖ Tool-motion system
- ❖ Finishing chamber

3.1.1 Power Supply System

ECH process generally uses a low DC voltage in the range of 3–30 volt with current adjustable up to 200A is applied across the inter electrode gap (IEG) between the anodic workpiece and cathodic tool and this gap is flooded with a suitable electrolyte. A computer controlled DC power supply unit (model 3300 W DC power supply) depicted in Fig 3.2 with capability of supplying an output voltage in the range of 0-100 V for low voltage units and high voltage 0-660 V for high voltage application, current in the range of 10-110 A and with computer controlled programmable options for setting pulse-on time and pulse-off time was used to supply the current in the IEG. It has programmable sequencer to use as an arbitrary waveform generator and create loops ramps and the sequencer is controlled via Ethernet programming. This enables it to supply constant and pulsed DC power supply for electrolytic dissolution process and flexibility for selecting best suitable parameters as per the requirement of the process. An oscilloscope (Fig 3.3) is a type of electronic test instrument that allows observation of constantly varying signal voltages, usually as a two-dimensional plot of one or more signals as a function of time. Other signals (such as sound or vibration) can be converted to voltages and displayed. It shows the values of rise and fall time which reveals the actual time taken in the electrolysis.



(a)



(b)

Fig. 3.1: Experimental apparatus developed for finishing of helical gear by PECH (a) schematic diagram; (b) photograph.

Fig. 3.2: Photograph of the pulsed power supply.

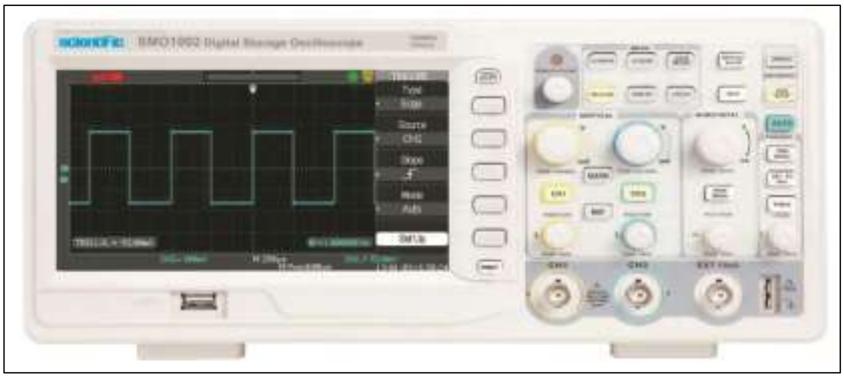
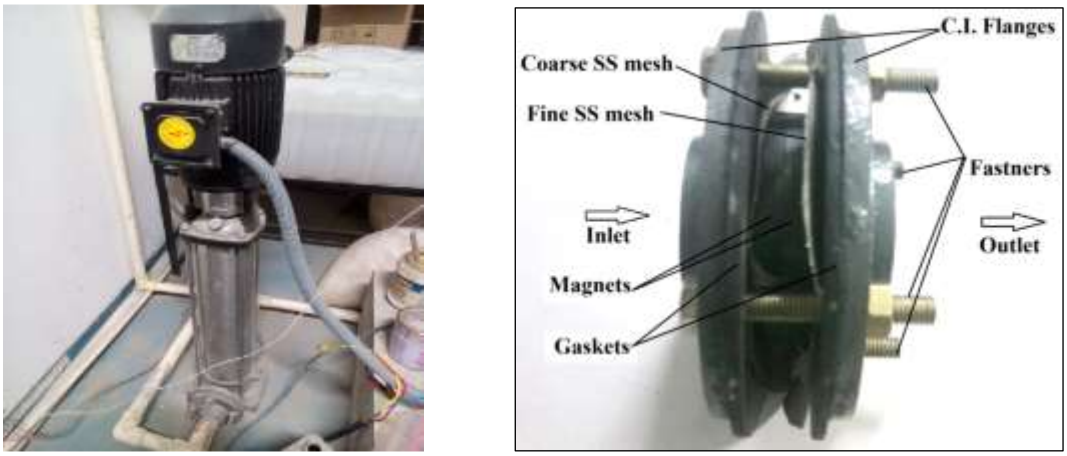


Fig. 3.3: Photograph of the oscilloscope.

The positive terminal of the power supply was connected to the shaft supporting the workpiece gear, while the negative terminal was connected to the cathode gears through carbon brush and slip ring assembly. Slip ring assembly for workpiece and cathode gears was mounted on the stainless steel shafts holding them.

3.1.2 Electrolyte Supply and Cleaning System

Electrolyte supply and recirculating system consists of electrolyte storage tank, settling tank, stainless steel pump (Fig. 3.4a), tubes for carrying electrolyte, flow-meter, flow control valves and constant temperature maintaining devices. It was designed to supply the required quality of filtered electrolyte to the finishing chamber at the desired flow rate, pressure and temperature and recirculate it back to the storage tank. An aqueous mixture of sodium nitrate ($NaNO_3$) and sodium chloride (NaCl) was selected as electrolyte keeping in view the materials of workpiece, honing and cathode gears. A PVC storage tank of 300 liters capacity was used to store and supply the electrolyte to the finishing chamber. The elevation of the storage tank was maintained in such a way that it ensures supply of the electrolyte required for the pump to start and to obtain a natural head for free return of the electrolyte from the finishing chamber. The electrolyte supply system contains two double-stages magnetic filters and stainless steel filters provided in the flow path of the electrolyte (Fig. 3.4b) for cleaning the electrolyte to ensure its purity. Pressure gauge (Fig. 3.5a) was used to measure electrolyte pressure and rotameter (Fig. 3.5b) was used to measure the flow of electrolyte. These devices were fitted in the electrolyte flow path. The electrolyte temperature was maintained by a heating element (Fig 3.6a) fitted with a precise temperature controller (Fig 3.6b) and a temperature sensor (Fig 3.6c). The temperature controller switches on or switch off the heating element based on the reading from the temperature sensor and the temperature set by the user.



(a) (b)

Fig. 3.4: Photograph of the (a) stainless steel pump for the flow of electrolyte; and (b) double-stages magnetic filters.

(a) (b)

Fig. 3.5: Photograph of the (a) stainless steel pressure gauge; and (b) rotameter.

(a) (b) (c)

Fig. 3.6: Photograph of the (a) heating element; (b); temperature controller and (c) temperature sensor.

3.1.3 Tool Motion System

Fabrication of tooling system of the experimental apparatus is the most crucial element. Tooling system performs functions such as (i) good coordination between mechanical and electrolytic actions of material removal from the workpiece gear; (ii) to direct and distribute the electrolyte in the inter-electrode gap so as to achieve maximum uniformity of electrolytic condition in the gap; and (iii) to provide the desired generating motion of simultaneous rotation and translation to the workpiece gear. It provides rotary motion to the workpiece gear by a DC motor fixed on the frame of a drilling machine. This motor has a controller to vary the rotary speed continuously. It provides reciprocating motion to the spindle of the bench drilling machine, which holds the workpiece gear, by a stepper motor with driver and a controller programmed by a software program from Copley Controls Corporation.

3.1.4 Finishing Chamber

Main task of the experimental apparatus was design and fabrication of the proper tooling system (i.e. cathode gear) and finishing chamber for finishing the helical gears by PECH process. It consists of (i) a specially cathode gear having an undercut conducting cathode gear sandwiched between two non-conducting gears for electrolyte dissolution and simultaneously maintain the required IEG; (ii) a honing gear for providing selective abrasion of passivating metal oxide micro-film formed over flank surfaces of the workpiece gear due to evolution of oxygen; (iii) the workpiece gear which is to be finished by the PECH process; (iv) provisions for supporting and mounting the workpiece, cathode and honing gears; (v) provisions for supplying DC pulse power supply between workpiece and cathode gears. Figure 3.7(a) shows photograph of the designed and developed finishing chamber. The workpiece gear was mounted on the spindle of a bench drilling machine which was provided rotary motion by a DC motor. Cathode and honing gear rotate due to their tight meshing with the workpiece gear. The cathode gear (Fig 3.7b) and honing gear (Fig 3.7c) were mounted on the stainless shafts (Fig. 3.7d) which were supported by the thrust ball bearings (Fig. 3.7e). Bakelite brackets were used to support and mount the bearings due to its excellent corrosion resistance, good electrical insulation and higher strength-to-weight ratio. Transparent sheets made of Perspex were used to fabricate the enclosure of this finishing chamber to provide better visibility of PECH process and due to its better corrosion resistance and strength-to-weight ratio.

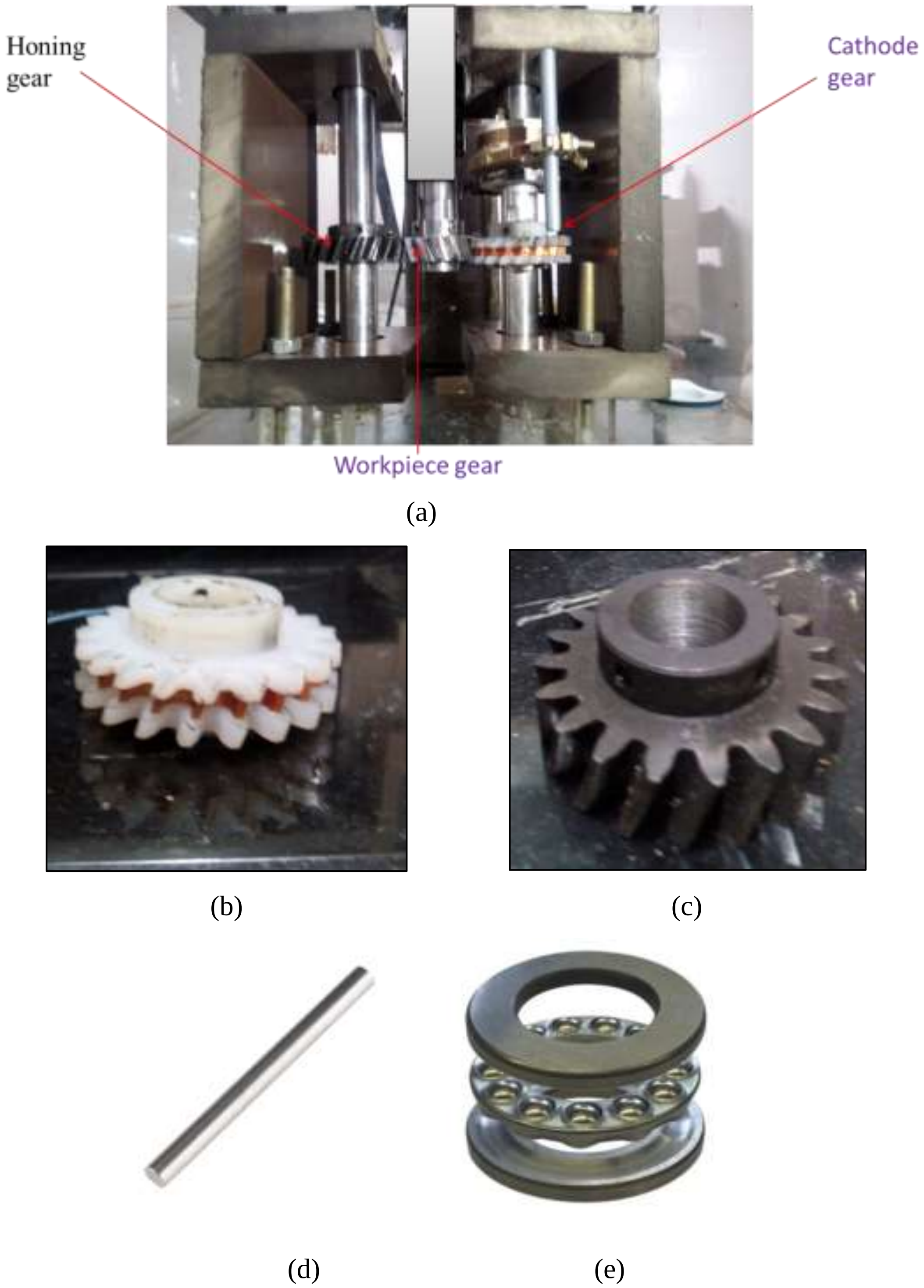


Fig. 3.7: Photograph of the (a) developed finishing chamber; (b) cathode gear having conducting layer sandwiched between the non-conducting layers; (c) honing gear; (d) shaft to mount gears; and (e) thrust bearing.

Since, ECH is a combination of ECM and honing and it involves electrolyte, electrical equipment, mechanical scrubbing, therefore design and selection of materials for various elements of the apparatus is based on some relevant considerations such as electrical conductivity, anti-corrosiveness, manufacturability, economics etc. Specifications of workpiece, honing, and cathode gears were selected on the basis of avoiding interference and undercutting of gears while meshing and for minimum noise during operation. Table 3.1 presents the details of the selected materials for workpiece, cathode and honing gears, their selection criteria and design specifications.

Table 3.1: Details of materials selected for different gears, their selection criteria and specifications.

Selected material	Selection criteria	Design specifications
Alloy steel 20MnCr5 for workpiece gear	• Since most of the material in PECH process is removed by PECF action, so workpiece material should be conductive in nature. • Alloy steel 20MnCr5 was selected as workpiece gear material due to its widespread commercial use for making helical gears for various industrial applications particularly in automobile industries.	Profile: Involute Module: 3 mm Pressure angle: 20^o No. of teeth: 15 Width: 15 mm Helix angle: 20^o (left hand helix) Hub dimensions OD: 45 mm; ID 25 mm; Width: 10 mm
Cathode gear [a] Copper for conductive portion [b] Metalon for non-conductive portion	• Copper has good electrical conductivity and machinability property. • Metalon has very good wear and corrosion and electrical resistance and easy machinability.	Profile: Involute Module: 3 mm Pressure angle: 20^o No. of teeth: 15 Width of copper and two Metalon layers: 5 mm Undercutting of Cu layer: 2 mm Helix angle: 20^o (right hand helix)
Hardened $20MnCr_5$ Alloy steel for the honing gear	• Better abrasive behaviour to scrap the passivating • To avoid the wear of honing gear while meshing. • For good life of honing gear	Profile: Involute Module: 3 mm Pressure angle: 20^o No. of teeth: 15 Width: 15 mm Helix angle: 20^o (right hand helix)

Next Chapter presents planning and details of experiments.

Chapter 4

Planning and Details of Experiments

According to the research objective, experiments were planned by using statistical approach of design of experiments. Taguchi L_{16} was used to design the experiments by varying four input parameters at four levels each. Voltage, pulse-on time, pulse-off time, and finishing time was considered as input parameters while concerned parameters of micro-geometry, surface roughness, and finishing productivity were chosen as performance measure of helical gears finished by PECH process.

4.1 Introduction to Design of Experiments

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.

4.1.1 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 2^k runs. Thus for 6 factors at two levels it would take 64 trial runs.

4.1.2 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.

4.2 Details of Experiments

Sixteen experiments were planned and conducted using Taguchi L_{16} orthogonal array experimental design. Pulse-on time (T_{on}), pulse-off time (T_{off}), finishing time (t) and voltage (V) were varied at four levels each with an objective to study their effects on the considered parameters of micro-geometry (i.e. total profile error, total lead error, cumulative pitch error and runout), surface roughness (in terms of average surface roughness, maximum surface roughness and depth of surface roughness), and finishing productivity in terms of volumetric material removal rate and to identify their optimum values. Values of other parameters of PECH process namely electrolyte composition (E); electrolyte concentration (C); electrolyte temperature (T); electrolyte flow rate (F); and rotary speed of workpiece gear (R) were kept constant on the basis of past works done on finishing of helical gears by ECH. Table 4.1 presents details of the variable and fixed input parameters used during the experiments.

Table 4.1: Details of variable and fixed input parameters used during experiments.

Variable input parameters	Levels				Values of the fixed input parameters
	I	II	III	IV	
Pulse on time 'T_{on}' (ms)	1.5	3	4.5	6	IEG: 2 mm; Electrolyte composition: 75% $NaNO_3$+25% NaCl Electrolyte concentration: 7.5 wt. % Electrolyte temperature: 32^{o}C Electrolyte flow rate: 30 lpm Rotary speed of workpiece gear: 40 rpm
Pulse-off time 'T_{off}' (ms)	3	6	9	12	
Finishing time (t) (minute)	2	4	6	8	
Voltage (V)	8	12	16	20	

4.2.1 Evaluation of Surface Roughness

Surface roughness significantly affects surface quality of a gear. Three parameters of surface roughness (i.e. average surface roughness 'R_a'; maximum surface roughness 'R_{max}' and depth of surface roughness 'R_z') were measured using 3D surface roughness-cum-contour-tracer from ***Mahr Metrology, Germany***. Measurements were taken along the pitch line on left hand and right hand flanks of gear teeth using 0.8 mm cut-off length and evaluation length of 2 mm. Arithmetic average of the measured values of a roughness parameter of an unfinished gear and the same gear finished by PECH were used to evaluate average percentage improvement in that parameter i.e. average percentage improvement in average surface roughness value 'PIR_a' can be calculated using Eq. 4.1.

$$Avg.\ PIR_a = \frac{Avg.\ R_a\, value\ of\ an\, unfinished\ gear - Avg. R_a\ value\ of\ the\ same\ gear\ finishined\ by\ PECH}{Avg. R_a\ value\ of\ the\, unfinished\ gear} 100(\%) \quad (4.1)$$

Similarly, average percentage improvements in maximum surface roughness 'PIR_{max}' and average percentage improvement in depth of surface roughness 'PIR_z' were also evaluated using their corresponding measured values. A higher value of percentage improvement in a roughness parameter infers lower value of that parameter after finishing by PECH process.

4.2.2 Evaluation of Micro-geometry

Micro-geometry of the helical gears was inspected in terms of their form errors [i.e. total profile error (F_a), total lead error (F_b)] and location errors [i.e. cumulative pitch error (F_p), and total runout (F_r)]. *Deutsche Normen* (DIN) and American Gear Manufacturers Association (AGMA) are the universally accepted standards for denoting quality of the gears in terms of 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 unfinished and PECH finished helical gears on the computer numeral controlled (CNC) gear metrology machine ***Smart-Gear*** from ***Wenzel Gear-Tec, Germany***. These values were used to compute average values of errors. Eq. (4.2) was used to compute average value of percentage improvement in total profile error (F_a).

$$Avg. PIF_a = \frac{Average\ Fa\ value\ of\ an\, unfinished\ gear - Average\ Favalue\ of\ the\ same\ gear\ finished\ by\ PECH}{Average\ Fa\ value\ of\ the\, unfinished\ gear} 100(\%) \quad (4.2)$$

Similarly, average values of percentage improvements were computed for error in total lead error (F_b) and cumulative pitch (PIF_p).

Concept of runout evaluation yields single value therefore percentage improvement in runout (PIF_r) was computed using Eq. 4.3.

$$PIF_r = \frac{F_r\ value\ of\ an\, unfinished\ gear - F_r\ value\ of\ the\ same\ gear\ finished\ by\ PECH}{F_r\ value\ of\ the\, unfinished\ gear} 100(\%) \quad (4.3)$$

Maximum value of percentage improvement in a micro-geometry parameter implies minimum value of that parameter after finishing the gear by PECH.

4.2.3 Evaluation of Finishing Productivity of PECH

Finishing productivity is a prime concern for every finishing process for their commercial adoption. In the present work, finishing productivity was evaluated in terms of average value of volumetric material removal rate (MRR) which was calculated by dividing the mass loss of the workpiece gear during its finishing by the PECH process by the product of the finishing time and density of the workpiece material (Eq. 4.4). Weight of the workpiece gear before and after finishing was measured on a precision weighing balance.

$$Avg.Vol.MRR = \frac{mass\ of\ an\ unfinished\ gear\ (gm) - mass\ of\ the\ same\ gear\ finishined\ by\ PECH\ (gm)}{Finishing\ time\ (s) \times Density\ of\ the\ workpiece\ material\ (gm/mm^3)} \left(\frac{mm^3}{s}\right) \quad (4.4)$$

4.3 Procedure of Experimentation

All the experiments were conducted using the following procedure:

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

Next Chapter describes the results and their discussion and results for the best finished gear.

Chapter 5

Results and Discussion

This chapter describes the results of the performed experiments, analyzes them and conclusions drawn from them.

5.1 Results

Table 5.1 presents the values and levels of input parameters along with the values of considered parameters of surface roughness in terms of average percentage improvements in (i) average surface roughness value 'PIR_a'; (ii) maximum surface roughness 'PIR_{max}'; and (iii) depth of surface roughness 'PIR_z'. While, Table 5.2 presents the same for considered parameters of micro-geometry in terms of average percentage improvements in (i) total profile error 'PIF_a'; (ii) total lead error 'PIF_b'; (iii) cumulative pitch error 'PIF_p'; (iv) runout 'PIF_r' and MRR. These tables also mentions combinations of four variable input parameters (i.e. pulse-on time 'T_{on}', pulse-off time 'T_{off}', finishing time 't' and voltage 'V') for different experiments.

It can be seen from Table 5.1 that the maximum values of average percentage improvements in average surface roughness (i.e. avg. PIR_a as 46.4%) attains during the experiment no. 1 while the maximum values of average percentage improvements in the maximum surface roughness (i.e. avg. PIR_{max} as 44.7%) and depth of surface roughness (i.e. avg. PIR_z as 47.4%) for the was achieved during experiment no. 2. From Table 5.2 it can be seen that the maximum values of average percentage improvements in total profile error (i.e. avg. PIF_a as 45.1%), total lead error (i.e. avg. PIF_b as 77.6%), cumulative pitch error (i.e. avg. PIF_p as 83.4%), and percentage improvement in runout (i.e. PIF_r 71.7%) was achieved for experiment no. 9, 11, 13 and 8 respectively. But, from Table 5.1 and 5.2 it can also be observed that the best combination for simultaneous improvements in concerned parameters of micro-geometry and surface roughness was found during the experiment no. 16 having values of finishing time as 8 minutes, pulse-on time as 6 ms, pulse-off time as 3 ms and applied voltage as 16 volts as input parameters. This combination of parameters caused improvement of 41.6% for avg. PIR_a; 32.3% for avg. PIR_{max}; 39.6% for avg. PIR_z; 41.7% for avg. PIF_a; -23.2 % for avg. 'PIF_b'; 74.7% for avg. PIF_p; and 47.8% for PIF_r. Finishing productivity in terms of volumetric material (i.e. 0.28 mm^3/sec) was also achieved during this combination. Considering the objective of simultaneous improvements in values of T_{on} as 6 ms, T_{off} as 3 ms, t as 8 minutes and V as 16 volts were identified as their optimum combination for attaining simultaneous improvement in considered parameters of surface roughness and micro-geometry. Following sections discuss effects of these parameters on the considered responses.

Table 5.1: Results of the experiments for surface roughness parameters.

Input variables					Parameters of surface roughness of helical gears								
					Average surface roughness (R_a)			Maximum surface roughness (R_{max})			Depth of surface roughness (R_z)		
Run no.	t (min)	T_{on} (ms)	T_{off} (ms)	V (volt)	Avg. value before PECH	Avg. value after PECH	Avg. PIR_a (%)	Avg. value before PECH	Avg. value after PECH	Avg. PIR_{max} (%)	Avg. value before PECH	Avg. value after PECH	Avg. PIR_z (%)
1	2	1.5	3	8	7.2	3.8	**46.4**	33.5	21.9	34.7	31.8	17.5	45.0
2	2	3	6	12	3.3	2.0	38.6	21.3	11.8	**44.7**	21.3	11.2	**47.4**
3	2	4.5	9	16	5.0	3.3	34.5	26.7	18.2	31.9	23.8	17.7	25.6
4	2	6	12	20	3.2	3.1	02.7	24.0	22.9	04.5	23.6	22.8	02.9
5	4	1.5	6	16	4.1	3.8	06.6	23.1	21.3	07.7	21.5	18.1	15.8
6	4	3	3	20	5.0	3.6	27.4	30.3	29.7	01.0	24.5	23.8	02.6
7	4	4.5	12	8	3.6	3.0	15.9	25.5	17.4	31.8	20.9	17.4	16.9
8	4	6	9	12	3.7	3.1	19.2	21.2	17.3	17.9	21.2	17.0	17.9
9	6	1.5	9	20	4.5	3.0	32.5	26.3	22.9	15.2	23.5	18.8	20.1
10	6	3	12	16	7.5	4.1	45.6	34.2	24.8	27.4	34.2	22.1	35.3
11	6	4.5	3	12	4.0	3.9	05.4	22.0	21.3	04.0	20.1	18.1	10.0
12	6	6	6	8	3.8	3.3	14.6	28.2	18.2	35.4	27.2	17.7	34.9
13	8	1.5	12	12	4.1	3.5	14.6	30.3	28.8	04.7	24.0	22.1	11.2
14	8	3	9	8	6.7	3.9	41.6	29.5	29.9	44.0	29.1	27.9	04.2
15	8	4.5	6	20	4.7	3.6	21.5	23.6	19.6	16.9	23.4	19.4	17.2
16	***8***	***6***	***3***	***16***	***7.0***	***4.1***	***41.6***	***36.6***	***24.8***	***32.3***	***36.6***	***22.1***	***39.6***

Table 5.2: Results of experiments for the micro-geometry parameters and MRR.

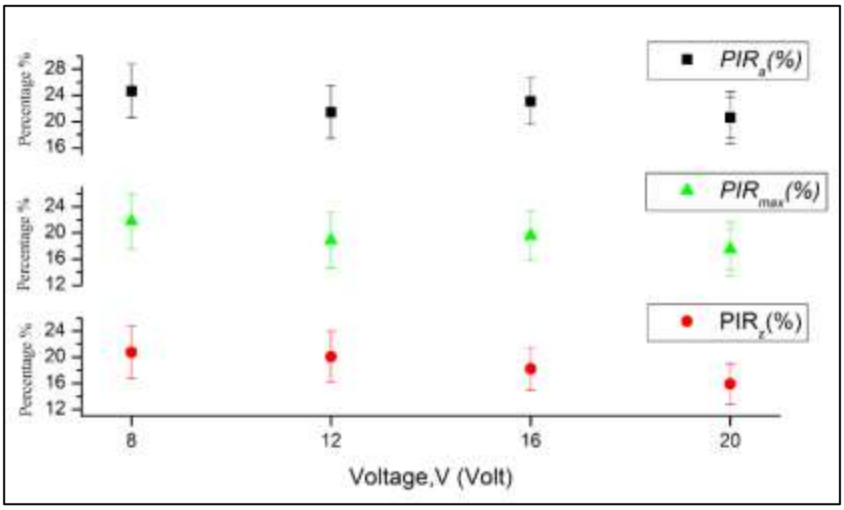
Input Parameters					**Total Profile error '*Fa*'(μm)**			**Total Lead error *'F_b'* (μm)**			**Total Pitch error *'F_p'* (μm)**			**Runout error *'F_r'* (μm)**			**MRR mm^3/sec**
Run no	***t* *(min)***	***T_{on}* (ms)**	***T_{off}* (ms)**	***V* *(volt)***	Avg. F_a before PECH	Avg F_a after PECH	***Avg. PIF_a (%)***	Avg. F_b before PECH	Avg. F_b after PECH	***Avg. PIF_b (%)***	Avg.F_p before PECH	Avg.F_p after PECH	***Avg. PIF_p (%)***	Avg.Fr before PECH	Avg.Fr after PECH	***Avg. PIF_r (%)***	
1	2	1.5	3	8	346.9	355.0	-02.3	360.2	178.7	50.3	319.7	600.6	-87.8	523.6	217.5	58.4	0.27
2	2	3	6	12	123.1	138.4	-12.4	218.6	260.0	-18.9	107.9	188.3	-74.4	266.7	102.7	61.4	0.31
3	2	4.5	9	16	122.7	102.0	16.8	133.0	240.4	-50.6	652.6	159.2	75.6	184.4	117.1	36.4	0.19
4	2	6	12	20	102.5	122.8	-19.7	285.4	133.1	53.3	159.0	260.6	-63.8	116.2	184.4	-58.6	0.21
5	4	1.5	6	16	107.8	120.5	-11.7	69.0	58.7	15.5	156.6	230.1	-46.9	215.0	261.1	-21.4	0.29
6	4	3	3	20	354.9	331.6	06.5	178.7	110.5	38.1	600.6	492.3	18.0	217.5	380.4	-74.8	0.32
7	4	4.5	12	8	195.8	115.0	41.2	95.2	118.3	-24.2	804.4	204.5	74.5	657.8	342.0	47.5	0.23
8	4	6	9	12	247.5	138.2	44.1	153.1	261.0	-70.4	602.7	651.2	-8.0	364.7	103.1	**71.7**	0.26
9	6	1.5	9	20	356.9	195.9	**45.1**	118.4	96.01	18.9	315.7	503.0	-59.3	732.9	656.1	10.4	0.29
10	6	3	12	16	331.6	357.0	-7.6	110.5	117.9	-6.6	492.3	316.0	35.8	1380.4	731.2	47.0	0.33
11	6	4.5	3	12	111.6	120.5	-7.9	261.4	58.4	**77.6**	370.3	230.2	37.8	187.3	260.9	-39.2	**0.34**
12	6	6	6	8	569.7	571.5	-0.3	183.9	303.6	-65.0	830.3	938.4	-9.8	71.5	30.0	58.0	0.27
13	8	1.5	12	12	138.2	123.2	10.8	260.6	218.5	16.1	651.9	108.0	**83.4**	102.4	200.3	-96.0	0.22
14	8	3	9	8	120.5	103.1	14.4	58.3	101.5	-74.0	230.1	160.1	30.4	261.1	116.1	55.6	0.28
15	8	4.5	6	20	115.1	108.1	6.1	117.3	68.9	41.2	203.5	157.0	22.7	341.5	214.9	37.1	0.31
16	***8***	***6***	***3***	***16***	***196.4***	***115.2***	***41.3***	***95.1***	***117.2***	***-23.2***	***804.4***	***203.3***	***74.7***	***656.2***	***342.0***	***47.8***	***0.28***

Figure 5.1 shows variation in *avg.* PIR_a , *avg.* PIR_{max} and avg. $PIRz$ [Fig. 5.1(a)] and variations in *avg.* PIF_a, *avg.* PIF_b, *avg.* PIF_p and PIF_r with applied voltage [Fig . 5.1(b)]. While Fig. 5.2-5.4 shows variations in the same with respect to pulse-on time [Fig. 5.2(a-b)], pulse-off time [Fig. 5.3(a-b)] and finishing time [Fig. 5.4(a-b)]. It can be observed from these graphs that simultaneous improvements in the considered parameters of surface roughness and micro-geometry occurs in the optimum ranges of voltage as 8-16 volts, T_{on} as 4.5-6 ms, T_{off} as 3-4.5 ms, and finishing time 't' as 4-8 minutes. These identified ranges of input parameters can be justified with the help of following discussions.

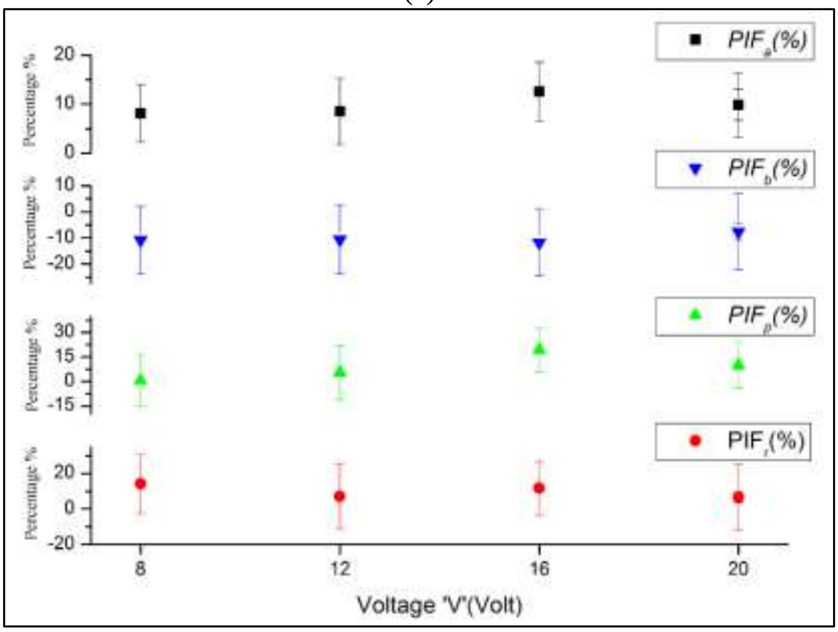
- **Effect of applied voltage:** From Figures 5.1(a-b) it is evident that the maximum values of average percentage improvements in considered parameters of micro-geometry increases with an increase in value of applied voltage upto 16 volts, while considered parameters of surface roughness attains its maximum values at lower values of voltage (i.e. 8 volts). But from Table 5.1-5.2 and Fig. 5.1(a-b) it can also be seen that the simultaneous improvement in considered parameters of both the major responses occurs at 16 volts as the values of applied voltage. This is due to the fact that at lower values of applied voltage the material removal rate is low which helps in reducing the surface roughness by minimizing the high peaks but the material removed at lower voltage was not sufficient to show any major changes in the micro-geometry of the helical gears. At higher values of applied voltage the higher material removal rate was observed which leads to non-uniform removal of material from the flank surface of the helical gears and thus deteriorates the surface finish and micro-geometry of the helical gears. Therefore a moderate value of applied voltage i.e. 16 volts is considered as optimum value to attain simultaneous improvement in all the considered parameters of surface roughness and micro-geometry.
- **Effect of pulse-on time and pulse-off time:** In PECH, material removal rate increases with an increase in duration of pulse-on time as it leads to give more time for the finishing action to occur. While, the role of pulse-off time is to take away all the reaction products and maintain a clean IEG for next cycle of pulse-on time. Therefore, a lower values of pulse-on time will give very less time for the finishing action and lead to give lower MRR which may correct the irregularities such as surface roughness but it may not be sufficient to correct the error related to micro-geometry errors. Therefore a higher value of pulse-on time i.e. 6 ms was considered as optimum value to attain simultaneous improvement in considered parameters of surface roughness and micro-geometry. Lower values of pulse-off time give sufficient amount of time to the finishing action to occur

and it also removes the generated sludge products in less time, therefore lower values of pulse-off time i.e. 3 ms was selected as optimum value of it.

❖ **Effect of finishing time:** Higher finishing time lead to give more finishing cycles which helps in getting higher material removal rate. Higher MRR helps in improving the errors related to profile related errors from the helical gear during its finishing by PECH. Therefore, higher values of finishing time i.e. 8 minutes was selected as optimum value of it to achieve simultaneous improvements in considered parameters of surface roughness and micro-geometry.

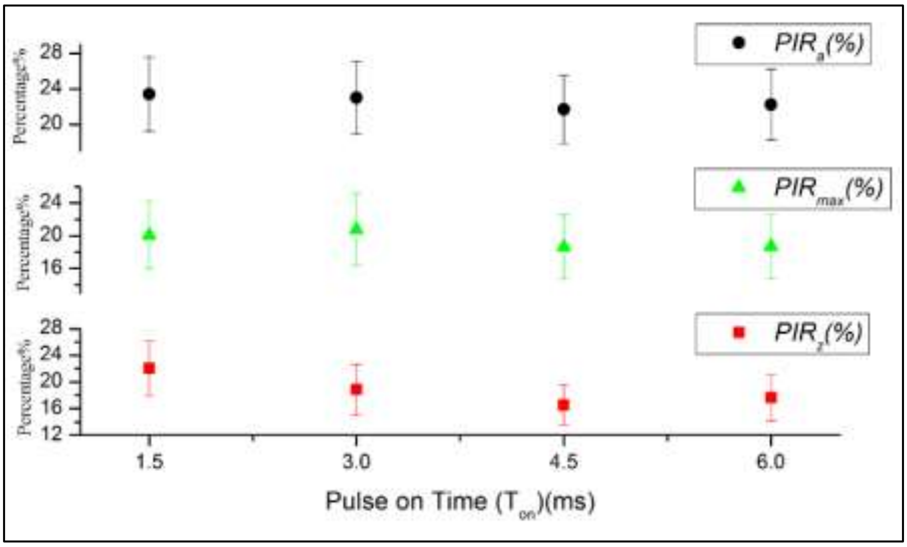


(a)



(b)

Fig. 5.1: Variations in (a) considered parameters of surface roughness; and (b) considered parameters of micro-geometry with applied voltage.



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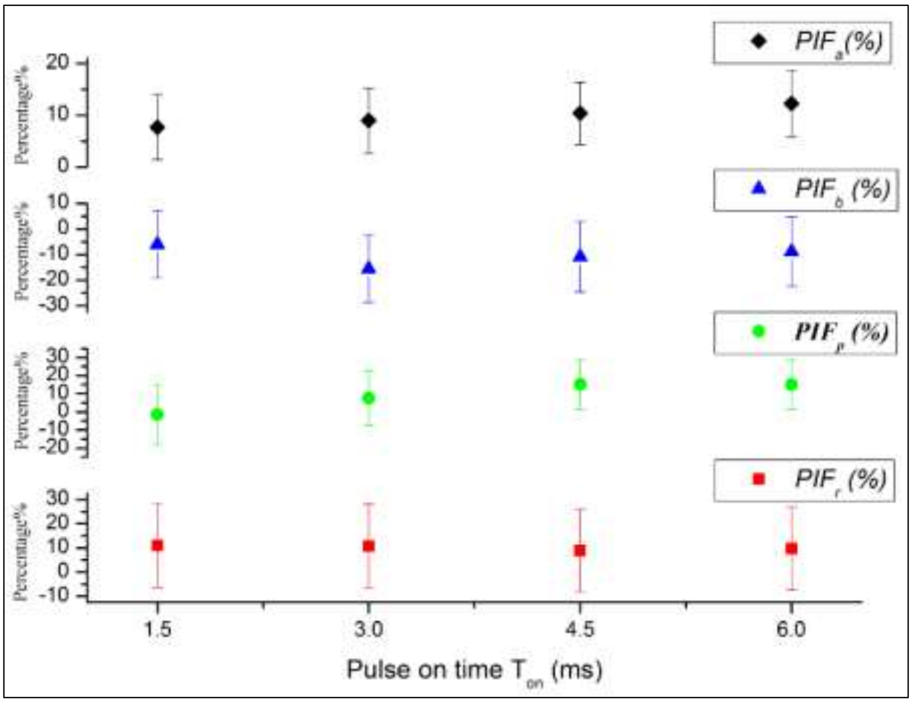
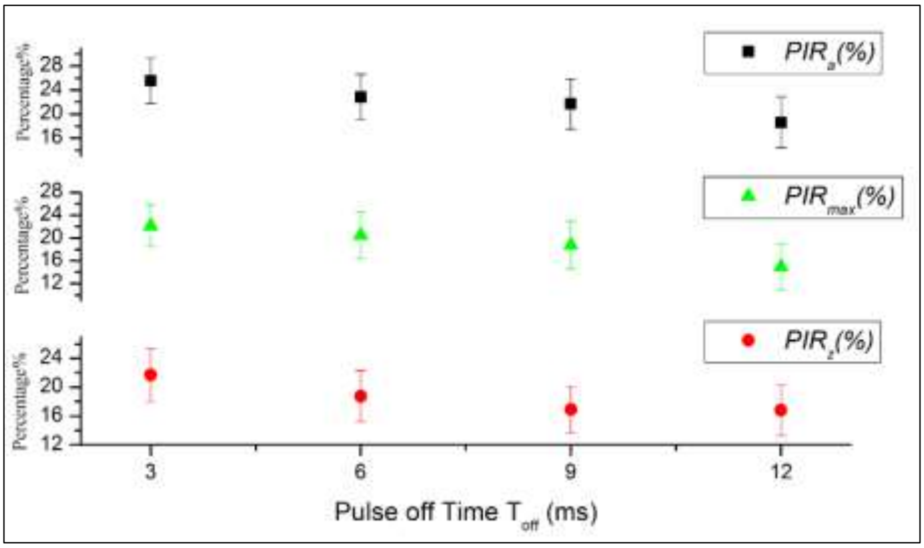


(b)

Fig. 5.2: Variations in (a) considered parameters of surface roughness; and (b) considered parameters of micro-geometry with pulse-on time.



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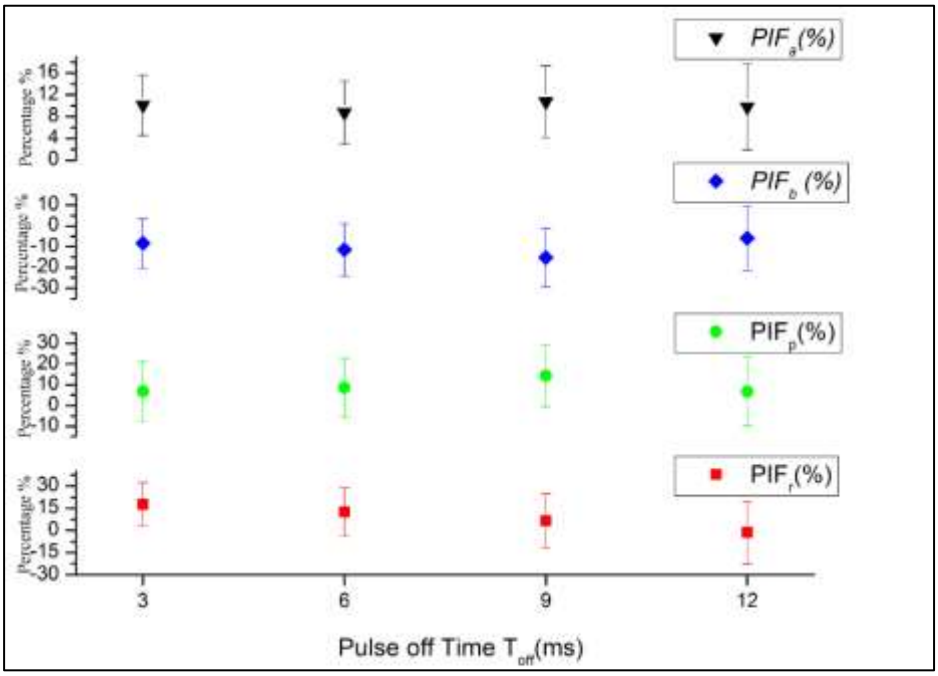
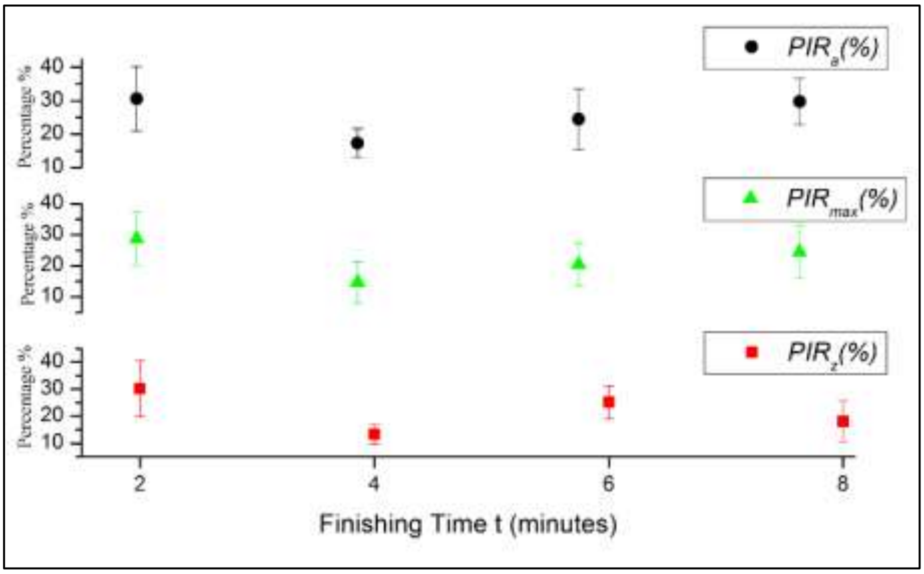
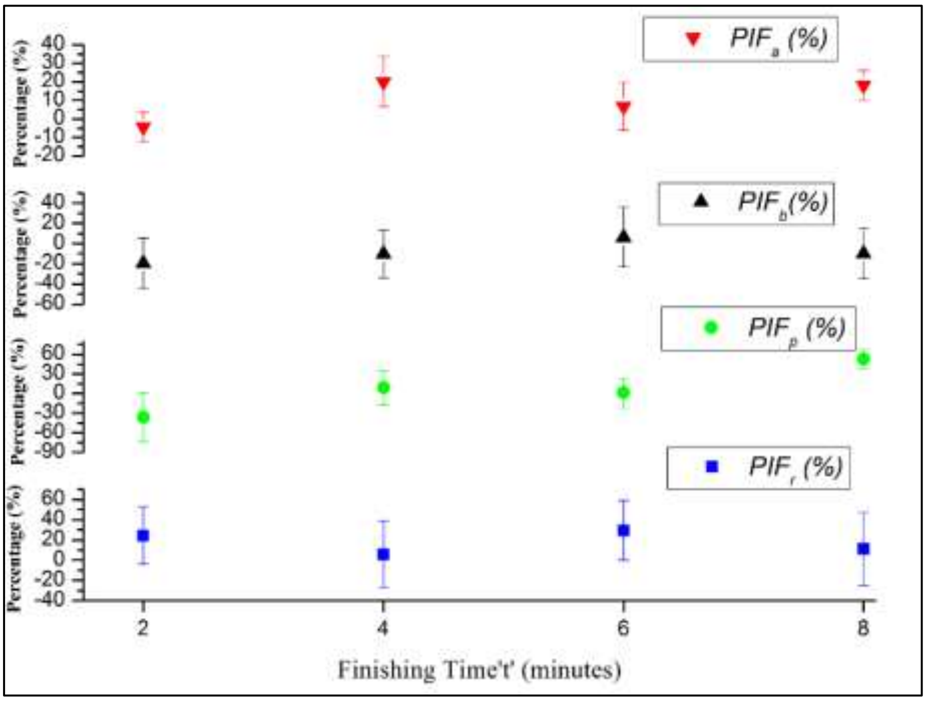


(b)

Fig. 5.3: Variations in (a) considered parameters of surface roughness; and (b) considered parameters of micro-geometry with pulse-off time.



(a)



(b)

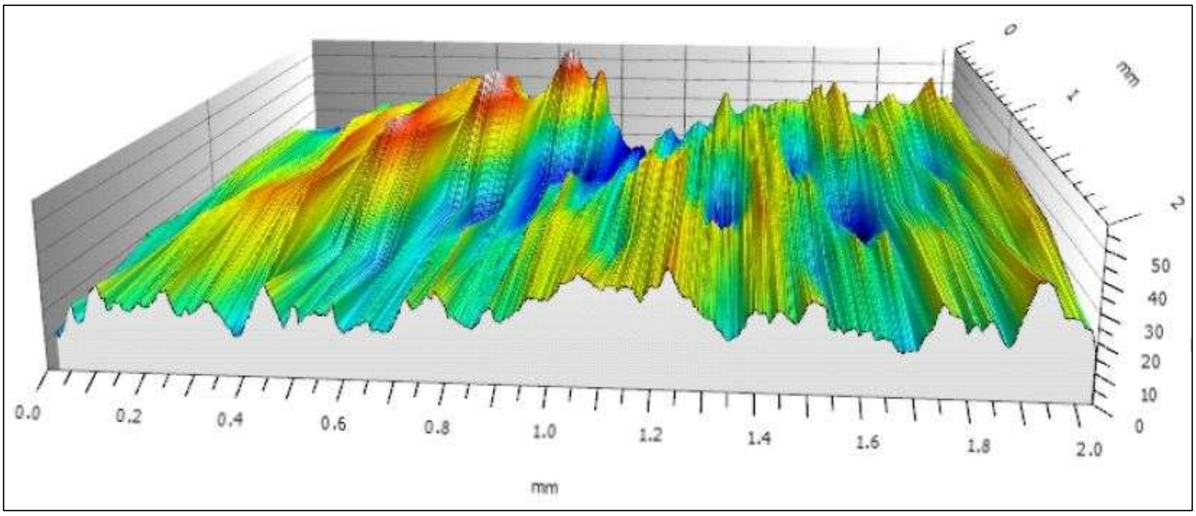
Fig. 5.4: Variations in (a) considered parameters of surface roughness; and (b) considered parameters of micro-geometry with finishing time.

5.2 Analysis of the Best Finished Gear

5.2.1 Surface Roughness

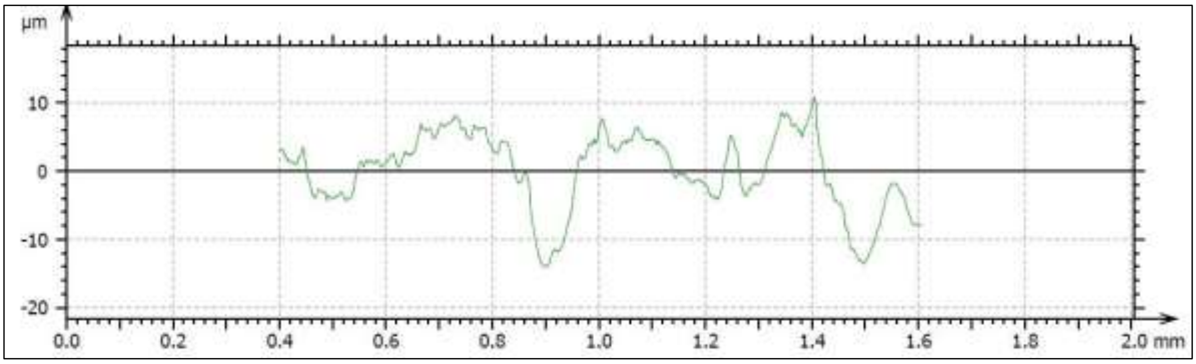
Figure 5.5 and 5.6 shows the surface roughness profile (i.e. variation of surface roughness along the evaluation length of 2 mm) of a particular tooth flank of an unfinished gear [Fig. 5.5] and of the same gear finished by PECH [Fig. 5.6] using the identified optimum values of pulse-on time, pulse-off time, finishing time and voltage (i.e. 6 ms; 3ms; 8 minutes and 16 volts respectively). It was found from these profiles that finishing a helical gear using the identified optimum values of pulse-on time, pulse-off time, finishing time and voltage by PECH reduced its maximum surface roughness (R_{max}) value from 36.6 to 24.8 µm; average surface roughness (R_a) value from 7.0 to 4.1 µm; and depth of surface roughness (R_z) from 36.6 to 22.1 µm.

(a)

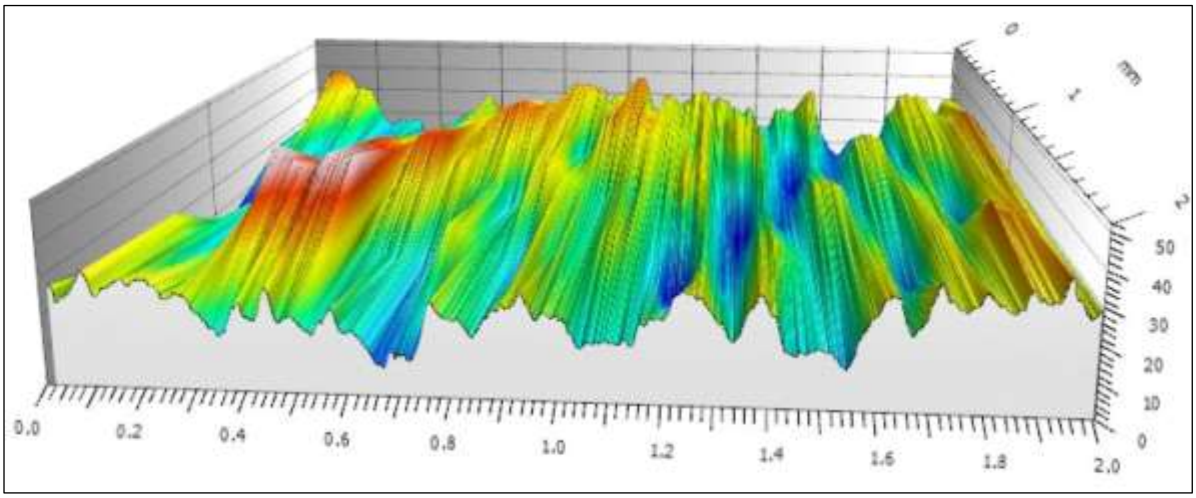


(b)

Fig. 5.5: (a) Roughness profile; and (b) 3D surface plot of gear tooth surface for an unfinished gear: using the identified optimum values of pulse-on time, pulse-off time, finishing time and voltage.



(a)

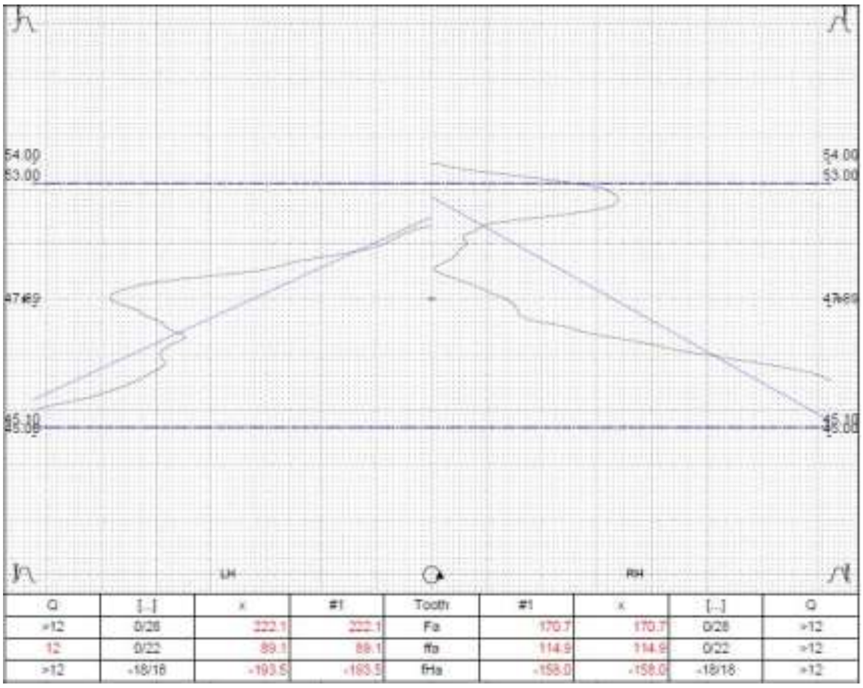


(b)

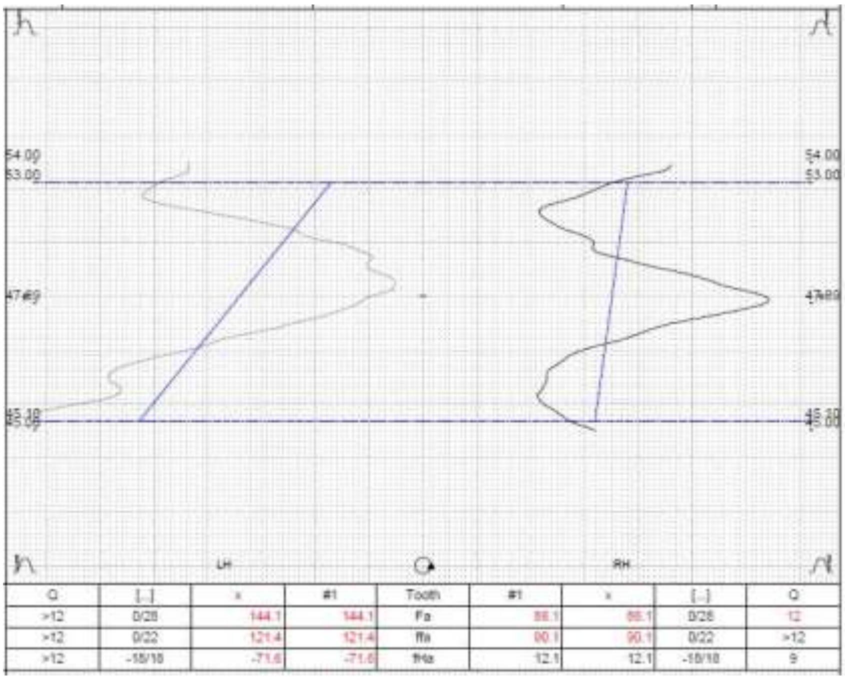
Fig. 5.6: (a) Roughness profile; and (b) 3D surface plot of gear tooth surface for a finished gear; using the identified optimum values of pulse-on time, pulse-off time, finishing time and voltage.

5.2.2 Micro-geometry

Figure 5.7 to 5.8 show the reports generated by the CNC gear metrology machine for total profile error 'F_a' and total lead error 'F_b' of helical gear before and after its finishing by PECH using the identified optimum parameters. It can be seen from the Figs. 5.7(a) and 5.7(b) that value of total profile error 'F_a' reduces from 196.4 to 115.2 µm giving 41.3% improvement in it. This improved the gear quality in DIN standard from greater than 12 to 12 for total profile error. It can be seen from the Figs. 5.8(a) and 5.8(b) that value of total lead error 'F_b' changes from 95.1 to 117.2 µm yielding -23.2% reduction in it. This reduced the gear quality. Figures 5.9 and 5.10 present the same for the cumulative pitch error and runout. It can be observed from Fig. 5.9 that finishing by PECH reduced cumulative pitch error 'F_p' of the best finished helical gear from 804.4 to 203.3 µm resulting 74.7% improvement in it. This improved the gear quality without any change in DIN standard for it. While runout 'F_r' reduced from 656.2 to 342 µm giving 47.8% improvement in it and this too improved the gear quality without any change in DIN standard for it.

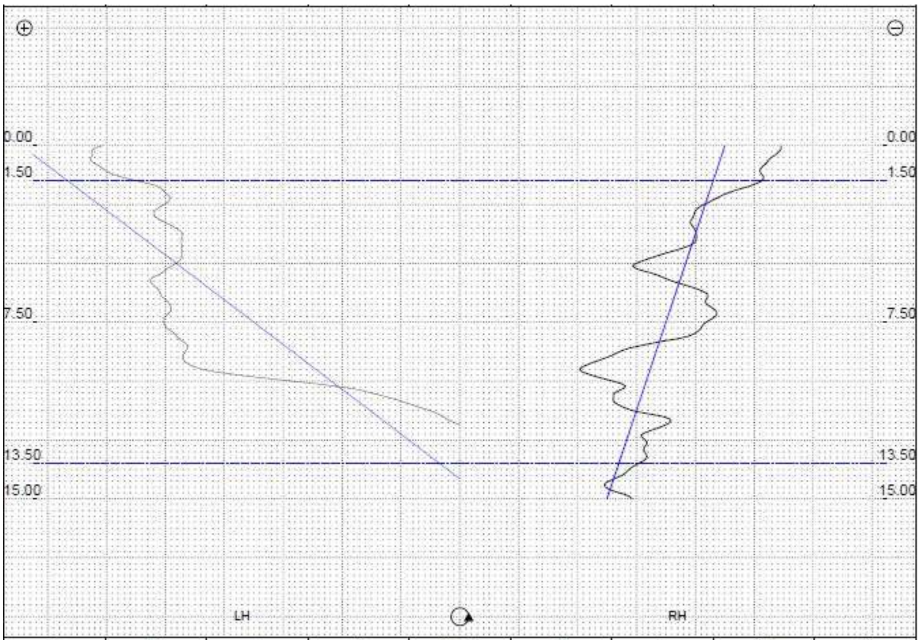


(a)



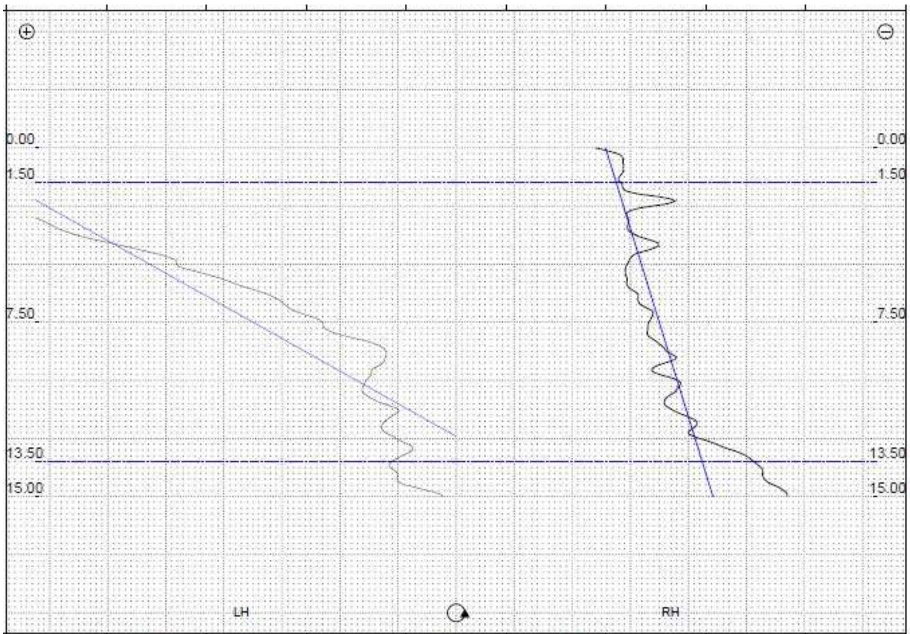
(b)

Fig. 5.7: Total profile error 'PIF_a' of gear (a) before finishing by PECH; and (b) after finishing by PECH using the identified optimum values of pulse-on time, pulse-off time, finishing time and voltage.



Q	[...]	x	#1	Tooth	#1	x	[...]	Q
>12	0/28	128.6	128.6	Fß	61.6	61.6	0/28	11
>12	0/14	71.7	71.7	ffß	40.3	40.3	0/14	12
>12	-25/25	157.9	157.9	fHß	-40.0	-40.0	-25/25	11

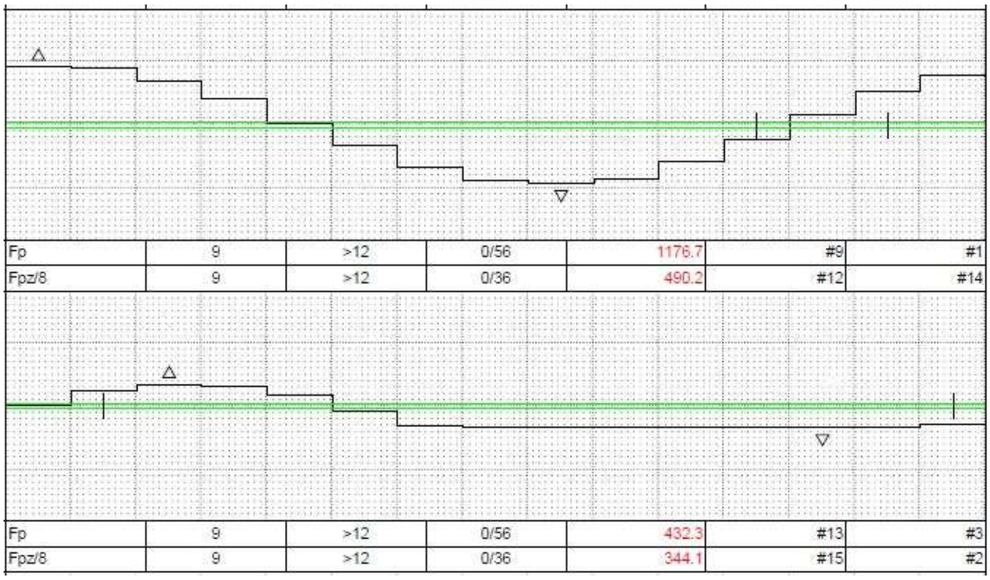
(a)



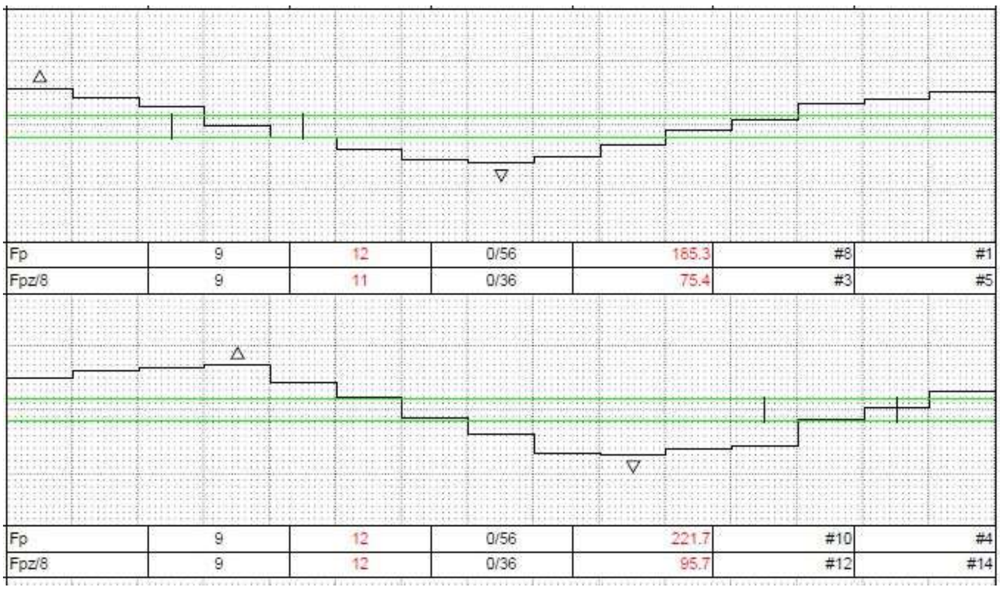
Q	[...]	x	#1	Tooth	#1	x	[...]	Q
>12	0/28	188.7	188.7	Fß	45.9	45.9	0/28	11
>12	0/14	77.1	77.1	ffß	26.0	26.0	0/14	11
>12	-25/25	213.9	213.9	fHß	37.0	37.0	-25/25	11

(b)

Fig. 5.8: Total lead error 'PIF_b' of gear (a) before finishing by PECH; and (b) after finishing by PECH using the identified optimum values of pulse-on time, pulse-off time, finishing time and voltage.

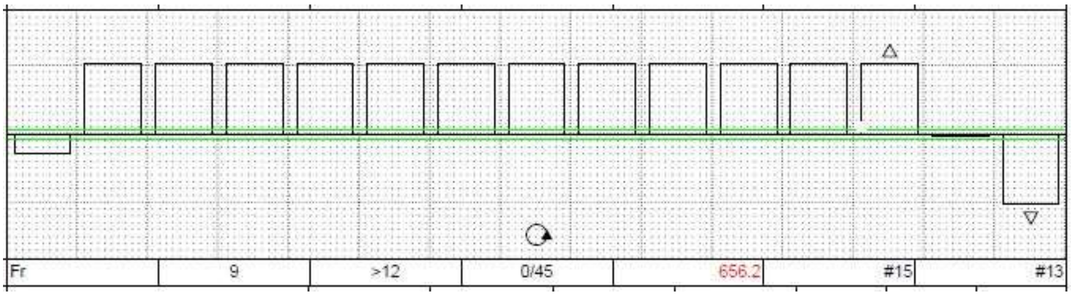


(a)

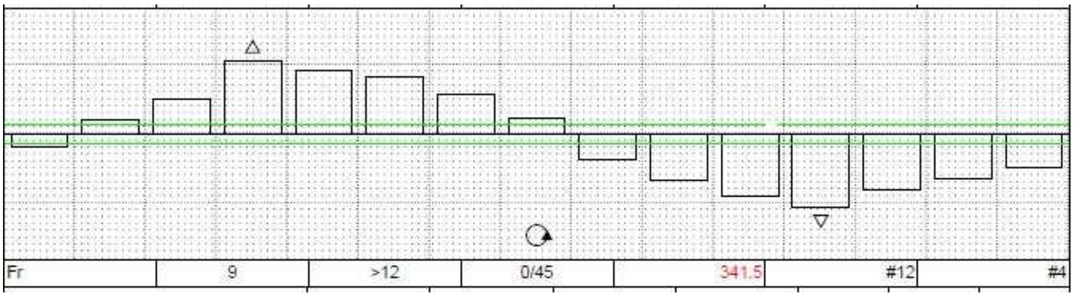


(b)

Fig. 5.9: Total pitch error 'PIF_p' of gear (a) before finishing by PECH; and (b) after finishing by PECH using the identified optimum values of pulse-on time, pulse-off time, finishing time and voltage.



(a)



(b)

Fig. 5.10: Runout *'F_r'* of gear (a) before finishing by PECH; and (b) after finishing by PECH using the identified optimum values of pulse-on time, pulse-off time, finishing time and voltage.

Next Chapter presents about conclusions and direction for future work.

Chapter 6

Conclusion and Scope for the Future Work

This chapter presents the conclusions of the present work along with mentioning directions for the future work.

6.1 Conclusions

Following conclusions are made after investigations on surface quality of helical gears finished by pulsed electrochemical honing.

- Study of effects of pulse-on time (T_{on}), pulse-off time (T_{off}), finishing time (t) and voltage (V) for simultaneous improvement in the considered parameters of surface roughness and micro-geometry and finishing productivity of PECH for the helical gears, identified their optimum values as 6ms; 3 ms, 8 minutes and 16 volts respectively.
- Use of the identified optimum values of T_{on}, T_{off}, t and V yielded the average values of PIR_a as 41.6%; PIR_{max} as 32.3% and PIR_z as 39.6%. Improvements in roughness parameters helps in better service life, improved operating performance, reduced noise and transmission error of the helical gears.
- It also improved the micro-geometry of the helical gear, yielding average values of PIF_a, PIF_b, PIF_p and PIF_r equal to 41.3 %; -23.2%, 74.7% and 47.8% respectively. Better micro-geometry helps in reducing the noise and transmission related error.

6.2 Directions for the Future Research

There is a sufficient scope for future work. Some of the directions for the future work are as follows:

- Development of theoretical models of volumetric material removal rate and depth of surface roughness for the helical gears finishing by PECH.
- Wear characteristics and functional testing of the helical gears by ECH/PECH processes.
- Noise and vibration testing of ECH/PECH finished gears.

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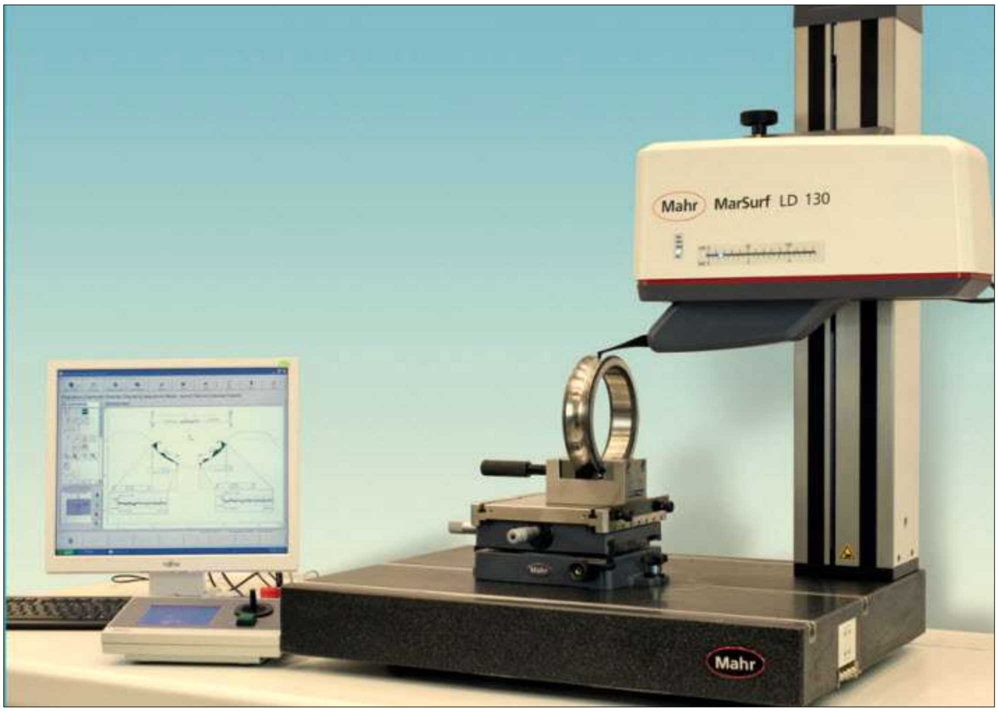
Appendix: Specifications of the Measuring Instruments

- **CNC Gear Metrology Machine (Center of Excellence in Gear Engineering, IIT Indore)**

Make: Wenzel GearTec, Germany	
Model: Smart 500	
External Gear Diameter Range: 5-270 mm	
Internal Diameter : >12 mm	
Range of Module: 0.4 – 15 mm	
Helix angle: <90°	
Accuracy for 3D measurement	MPE_e: 4.5+L/250 µm
	MPE_p: 4.5 µm
	MPE_{thp}: 5 µm

Surface Roughness-cum-Contour Tracer

- **3D Surface Roughness-cum-Contour Tracer (Center of Excellence in Gear Engineering, IIT Indore)**



Make: Mahr Metrology, Germany
Model: LD-130 with XT Facility
Tracing length: 0.1 mm to 130 mm
Inclination of the measuring stand: ±45°; without active adjustment of the measuring force
Resolution: 0.8 nm