Investigations on the Performance Characteristics of Straight Bevel Gears by Pulsed Electrochemical Honing (PECH) Process

Ph.D. Thesis

By

Sunil Pathak

Discipline of Mechanical Engineering

Indian Institute of Technology Indore

April 2016

Investigations on the Performance Characteristics of Straight Bevel Gears by Pulsed Electrochemical Honing (PECH) Process

A Thesis

Submitted in partial fulfillment of the

requirements for the award of the degree

of

Doctor of Philosophy

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Candidate's Declaration

I hereby certify that the work which is being presented in the thesis entitled **Investigations on the Performance Characteristics of Straight Bevel Gears by Pulsed Electrochemical Honing (PECH) Process,** in the partial fulfillment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY** 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 **Jan 2013 to April 2016** under the supervision of **Prof. 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.

(Sunil Pathak)

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)**

Sunil Pathak has successfully completed his Ph.D. Oral Examination held on **……….**

Signature of Thesis Supervisors
Date:

Signature of Convener, DPGC
Date:

Signature of PSPC Members
Date:

Signature of External Examiner
Date:

Signature (with date) of Chairman of PhD Oral Examination Board

Acknowledgements

First and Foremost, I would like to thank my supervisors **Prof. N. K. Jain** and **Dr. I. A. Palani** for providing me with the opportunity to complete my PhD thesis at **Indian Institute of Technology, Indore**. As my supervisors, they have constantly forced me to remain focused towards achieving my goal. Their observations and comments helped me to establish the overall direction of the research and to move forward with investigation in depth. I am very grateful for their patience, motivation, enthusiasm, and immense knowledge in advanced machining processes and especially in gear engineering that taken together, make them a great mentor.

I am extremely happy to express my gratitude towards my PSPC members **Dr. Anand Parey** and **Dr. Trapti Jain** for their guidance and cooperation. I am grateful to the **Prof. Pradeep Mathur, Director**, **IIT Indore** and **faculty members** of Discipline of **Mechanical Engineering** for providing the essential facilities and guidance.

I want to thank past scholars of the Gear Research lab **Dr. Javed Habib Sheikh** and **Dr. Kapil Gupta** for giving me an introduction into the Gear Research and for sharing their knowledge and expertise. I would also like to thank and express my gratitude towards **Mr. Balmukund Dhakad** and **Dr. Suyog Jhavar** for motivating me and helping me during the tough phases of my research. Special thanks to my friends of IIT Indore **Dr. Harimohan Kushwaha**, **Yogesh Madaria**, **Vinod Singh**, **Amit Kumar Jain, Vikas Sharma**, **Ankur Saxena**, **Sujeet Choubey**, **Mayur Sawant**, **Sagar Nikam**, **Naresh Raghuvanshi**, **Saurabh Yadav**, **Tameshwar Nath Tiwari, Shiva, Akash K. Muneer Alam**, **Swagat Dwivedi** and **Praveen Rai** for giving me company and comments despite of their busy schedules during tea breaks.

I am very thankful to **Sophisticated Instrumentation Center (SIC), Center of Excellence in Gear Engineering**, **Advanced Manufacturing Processes (AMP) Lab, Unconventional Machining Processes (UMP) Lab, Tribology Lab, Solid Mechanics Lab and Central Workshop of IIT Indore, Volvo Eicher Commercial Vehicles (VECV)**, Pithampur and AVTEC Pithampur for allowing me to use their machines and measuring instruments. I express my gratitude towards **FCIPT**, Gandhinagar for allowing me to use its plasma nitriding facility.

I am also thankful to Lab staff of Mechanical Engineering Labs and Central Workshop, specially **Sh. Anand Petare ASW, IIT Indore, Sh. Santosh Sharma and Sh. Sandeep Gour, Mr. Virendra Tak** (former Machine Operator Workshop)**, Mr. Deepak Rathore** (WEDM Machine Operator), for their cooperation in fabrication of my experimental setup.

I acknowledge and thankful to **MHRD, Govt. of India** for providing fellowship to pursue my doctoral studies.

Last, but not least, I would like to dedicate this thesis to **my parents**, **sisters** and **my caring wife *Swati***, for their love, patience, and understanding. They allowed me to spend most of the time on my thesis, without which this journey would not have been possible**.**

Sunil Pathak

Dedicated

to

My Family

Abstract

Conical gears are used for transmitting power and/or motion between the intersecting shafts (i.e. straight and spiral bevel gears) or the non-parallel non-intersecting shafts (i.e. hypoid gears). Among these straight and spiral bevel gears are extensively used in the automobiles, aerospace, marine, machine tools, construction machinery, wind turbine, equipment used in the process, cement, steel, oil and gas industries, etc. Increasing demands of gears have motivated researcher to investigate and improve their performance characteristics using different conventional and advanced gear finishing processes. Performance characteristics of a gear include its load carrying capacity, service life, operating performance, surface characteristics, wear characteristics, transmission characteristics and noise generation characteristics. Most of the performance characteristics of gear namely service life, operating performance and characteristics related to wear, transmission and noise generation are significantly affected by surface characteristics of a gear. It has two major components namely (i) surface quality which includes surface finish, micro-geometry (i.e. form and location errors) and wear characteristics; and (ii) surface integrity that encompasses microstructure, micro-hardness and residual stresses.

Improving surface characteristics of the bevel gears is very challenging and difficult due to complex geometry of their teeth. Gear grinding and lapping are the most commonly used conventional processes for finishing the bevel gears. But, these processes have some inherent limitations. Gear grinding is expensive in terms of initial investments and regular maintenance of the grinding wheels. It is laborious and highly skilled operator is required to perform the finishing operation. Also, form or generation grinding by a single formed wheel (or two single formed wheels) is time consuming. Moreover, Karpuschewski ***et al.*** (2008) highlight that it can also lead to undesirable effects such as (i) transverse grind lines on the finished surface which cause noise and vibration of the gears, (ii) grinding burns which damage the surface integrity of the ground gears and can sometime lead to even gear failure through tooth breakage. While, gear lapping is very slow finishing and used to finish a conjugate pair of gears. It can rectify only minute deviations from the desired gear tooth profile. Moreover, longer lapping cycle may affect the tooth flank profile and thus extensive care during the operation is required.

It is evident that non-overlapping and limited capabilities and inherent limitations of the conventional processes of gear finishing do not allow a single process to simultaneously improve all the surface characteristics of any gear material and without inducing any

adverse effect. Most of the time, a combination of conventional finishing processes is required to achieve the required surface quality which become very time consuming and laborious and affects the requirement of high productivity. These limitations can be overcome by developing a non-contact, material hardness independent, more productive, more economical and a sustainable gear finishing process.

Pulsed electrochemical honing (PECH) is a hybrid super finishing process which combines capabilities and advantages of pulsed electrochemical finishing (PECF) with mechanical honing and simultaneously overcoming their individual limitations. Main capabilities of PECF process include: process performance independent of mechanical properties which imparts it 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 PECF 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. PECH has been evolving as one of the most promising superfinishing techniques to finish the complex shaped engineering components. This makes PECH as an ideal choice to explore as an alternative, superior and economical process for gear finishing.

The present research work is focused on improving the performance characteristics of the straight bevel gear made of 20MnCr5 alloy steel by PECH with on objective to develop PECH as a better, productive and economic alternative process for fine-finishing of bevel gears. It was done by:

- Developing an innovative experimental setup based on the concept of twin complementary cathode gears for simultaneous improvements surface quality and surface integrity of all the teeth of a straight bevel gear.
- Studying the effects of eight PECH parameters namely pulse-on time, pulse-off time, applied voltage, composition, concentration and flow rate of the electrolyte, rotary speed of the workpiece gear and finishing time on the surface quality, surface integrity and MRR of the PECH finished gears.

- Studying the role of honing role hardness on surface quality and surface integrity of the PECH finished gears.
- A comparative study on specific energy consumption for achieving same level of finishing through ECH and PECH.
- Comparative study of PECH with ECH to prove the usefulness of pulse power supply in ECH process and PECH with PECF to prove importance of hybridization in improving the process performance of PECH.

Numerous experiments in different stages have been performed to achieve the above mentioned research goals and to identify the optimum values of the input parameters for simultaneous improvement in (i) surface quality in terms of surface roughness (i.e. average surface roughness, maximum surface roughness, depth of surface roughness), micro-geometry (i.e. single pitch error, adjacent pitch error, cumulative pitch error and runout), flank surface topology, and wear characteristics (i.e. coefficient of friction and friction force); and (ii) surface integrity in terms of microstructure, micro-hardness and residual stresses. Following conclusion have been made from the present research work:

- Results have shown significant improvements in the measured responses on using the identified optimum combination of different PECH parameters namely: pulse-on time as 2 ms, pulse-off time as 4.5 ms, electrolyte composition as 75 wt. % NaCl + 25 wt. % $NaNO_3$, electrolyte concentration as 7.5 wt. %, electrolyte flow rate as 20 lpm, rotary speed of the workpiece gear as 40 RPM and finishing time as 6 minutes to attain simultaneous improvements in surface finish and micro-geometry parameters.
- Role of Honing Gear Hardness: The present study finds new and important parameters of PECH i.e. hardness of honing gear.
- Sustainability of PECH: The present study reveals that PECH is sustainable and energy-efficient process as compared to the ECH process.
- Material Removal Mechanism and Modeling: The present study also describes the mechanism of generation of passivation layer and role of honing gear in removing it, which helps in better understanding of hybridization of ECF and mechanical honing.
- Mathematical models have been developed for prediction of MRR and depth of surface roughness of bevel gear finished by PECH.
- Results of validation experiments showed very close agreement between the model-predicted values of volumetric MRR and depth of surface roughness and their corresponding experimental values.

Synopsis

Gear is a modified form of a wheel. It is one of the basic machine elements used for transmission of power and/or motion between two parallel shafts (cylindrical gears i.e. spur and helical), intersecting shafts (conical gears i.e. straight and spiral bevel) and non-parallel and non-intersecting shafts (i.e. hypoid gears and worm and worm-wheel). Gear drives are preferred for various power and/or motion transmission purposes due to their compactness and higher reliability. More than 10 billion gears are manufactured and consumed annually in various applications in almost all the industries. Some worth-mentioning sectors that consume majority of gears are automobiles (i.e. cars, trucks, tractor, motor-cycles, scooter, etc.), means of transportation (i.e. buses, train, subways, mine cars, 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, tanks, radar application), earth moving machinery, different types of machine tools, oil and gas industry (i.e. oil platforms, pumping station, drilling sites, refineries and power stations), industrial applications (i.e. power transmission; construction equipment, agriculture machinery, equipment and machines used in mining, cement manufacturing, steel manufacturing, food processing, sugar manufacturing and other industries), home appliances (i.e. washing machine, food mixtures, fans, etc.), mechanisms, toys, gadgets, etc. Continuous requirements of gears and advancements in their applications compel manufacturing gears of higher quality, accuracy and reliability.

Performance characteristics of a gear include its load carrying capacity, service life, operating performance, surface characteristics, wear characteristics, transmission characteristics and noise generation characteristics. Most of the performance characteristics of gear namely service life, operating performance and characteristics related to wear, transmission and noise generation are significantly affected by surface characteristics of a gear. It has two major components namely (i) surface quality which includes surface finish, micro-geometry (i.e. form and location errors) and wear characteristics; and (ii) surface integrity that encompasses microstructure, micro-hardness and residual stresses. Errors in surface characteristics lead to premature failure of gears and its prevention requires understanding the interrelationship between following factors: (i) shape or geometry of gear tooth; (ii) forces (static and dynamic) on gear tooth; (iii) motion of gear tooth; (iv) gear material; (v) physical and chemical characteristics of the lubricant; (vi) operating environment; and (vii) surface quality and surface integrity of gear tooth. First six items are related to design and application environment of the gears, whereas surface quality and surface integrity of gears depends on finishing of the gears.

An unfinished gear generally has poor surface characteristics and fails to meet the requirement of the end users. This leads to noise generation, errors in transmission characteristics, excessive wear and backlash between the meshing gears. Consequently, gear teeth should be finished properly to ensure efficient motion transmission, noiseless operation, longer service life, better operating performance and enhanced load carrying capacity. Karpuschewski et al. (2008) have highlighted two major goals that a gear finishing process should fulfil namely: (i) surface quality improvement and reduction in form errors to maximize load carrying capacity; and (ii) surface integrity improvement and flank modifications to minimize the running noise. This can be ensured by a suitable combination of gear finishing and gear flank surface properties enhancing process (es). Gear shaving, gear honing, gear burnishing, gear grinding and gear lapping are the conventional finishing processes for gears. Finishing of conical gears is very difficult and challenging as compared to that of cylindrical gears due to their complex tooth geometry and only gear grinding and gear lapping can be used for finishing them. But, these processes also yield some undesired effects as mentioned by Karpuschewski et al. (2008). Gear grinding produces two major undesirable effects namely: transverse grind lines on the flank surface which causes noise generation and vibration of the gears and grinding burns which damage the surface integrity of the ground gears which can even sometime lead to gear failure through tooth breakage. Moreover, it is expensive, complicated, less productive and requires skilled labor. Gear lapping finishes gears in a conjugate pair and can rectify only minute deviations in the micro-geometry. Being a slow process, it requires longer lapping cycles which adversely affects gear micro-geometry.

It can be concluded that non-overlapping and limited capabilities and inherent limitations of the conventional processes of gear finishing do not allow a single process to improve all the surface characteristics of any gear simultaneously without inducing any adverse effect. Most of the time, a combination of conventional finishing processes is required to achieve the required surface quality of a gear which become very time consuming, laborious and reduces productivity. These limitations can be overcome by developing a non-contact and sustainable gear finishing process which is independent of mechanical properties of gear material.

Pulsed Electrochemical Honing (PECH) is a hybrid super finishing process which combines capabilities and advantages of pulsed electrochemical finishing (PECF) with mechanical honing and simultaneously overcoming their individual limitations. Main capabilities of PECF process include: finishing capabilities being independent of mechanical properties of gear material particularly hardness, production of stress-free and crack-free surface, higher material removal rate (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 PECF process is passivation of anodic workpiece surface by the metal oxides formed due to evolution of oxygen gas at anode during its electrolytic dissolution. Passivation of anode prohibits further electrolytic dissolution of the workpiece. While, major limitations of honing process are: incapability of finishing a hard or hardened workpiece material, low productivity, possibility of mechanical damage (i.e. micro-cracks, hardness alternation and plastic deformation) to the workpiece material and limited life of honing tool. This makes PECH as an ideal choice to explore as an alternative, superior and economical process for gear finishing. Fig. 1 shows the surface characteristics of a gear that can be improved by finishing it by PECH process.

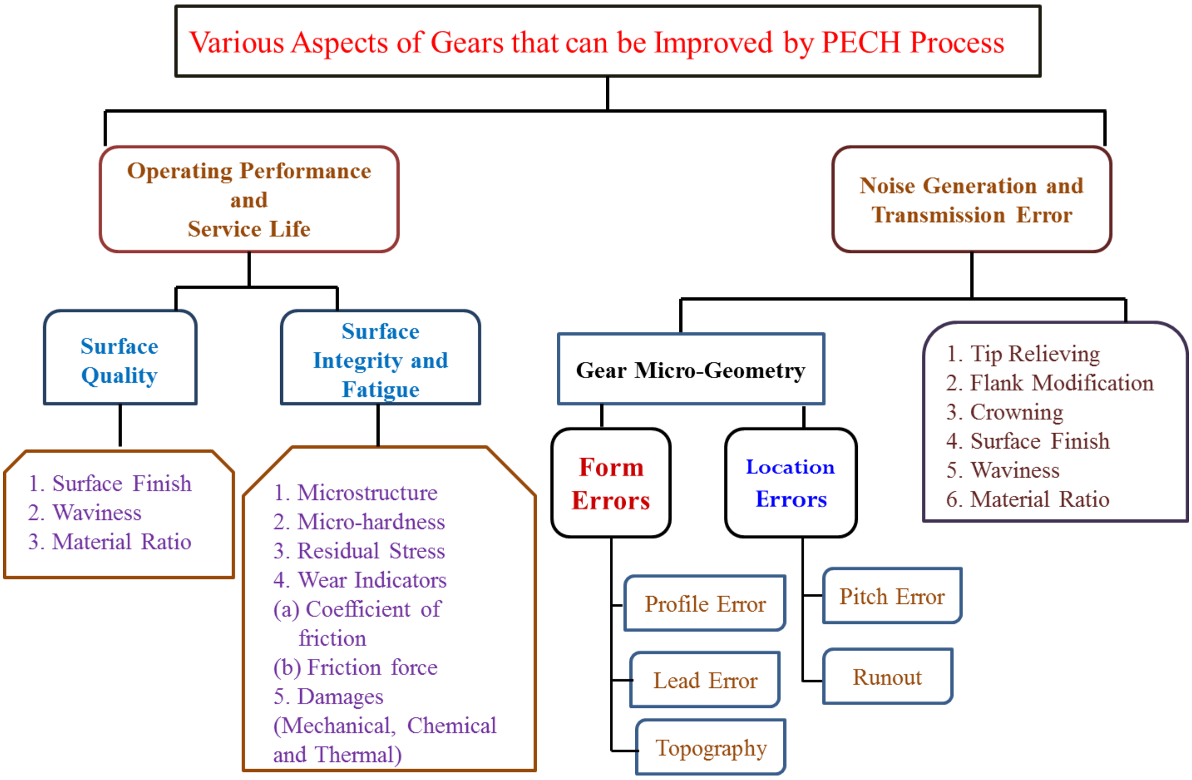


Fig. 1. Surface characteristics of a gear that can be improved by its finishing by PECH.

Brief Review of Past work on ECH: Development of ECH for finishing of gear was initiated very first time by **Capello and Bertoglio (1979)**. They designed and developed an experimental apparatus of ECH to finish hardened *helical* gears using specially designed cathode in the form of a helical gear. Though their results did not yield satisfactory improvement in micro-geometry of the ECH-finished helical gears but they successfully demonstrated potential of ECH to be developed as an alternative gear finishing process. **Chen *et al.* (1981)** developed an experimental apparatus for finishing the *spur* gears by ECH using the concept of sandwiching conducting layer between two non-conducting layers in the cathode gear to ensure finishing by ECH. They reported improvement in the surface finish, teeth profile accuracy and reduction in noise level. **He *et al.* (2000)** used electrolysis time-control method to correct the gear tooth profile errors very efficiently in the process that they referred as slow-scanning field controlled ECH (SSFC-ECH) of gears. **Naik *et al.* (2008)** used ECH to finish *spur* gears and reported percentage improvement in surface roughness parameters i.e. average surface roughness and maximum surface roughness as 80 % and 67 % respectively. **Misra *et al.* (2010)** used ECH for finishing the *helical* gears made of EN8 and reported 94 % and 86 % improvements in average surface roughness and maximum surface roughness respectively. **Shaikh (2014a)** was probably the first researcher to explore ECH for finishing of conical gears (i.e. straight bevel gear) envisaging a novel concept of complementary cathode gears to meet challenges of straight bevel gear finishing by ECH. He reported 62.7 % and 32.7 % improvements in average surface roughness and maximum surface roughness respectively. He also developed mathematical models for material removal rate (MRR) and surface roughness in ECH process and validated them.

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 finishing of the conical gears (i.e. straight bevel gears) by PECH process focussing on their performance characteristics in terms of surface quality [(in terms of surface roughness, material ratio curve, waviness, micro-geometry, gear tooth flank topology and wear characteristics (i.e. wear rate, coefficient of sliding friction, frictional force,)], surface integrity (i.e. micro-hardness, microstructure and residual stresses) and functional characteristics.
- ✓ No work has been reported on simultaneous improvement of all the factors affecting surface characteristics of bevel gears to improve their operating performance, service life and reduce noise generation.
- ✓ No work has been reported on studying and identifying the role of honing gear hardness in finishing of gears by PECH.
- ✓ No work has been reported on theoretical prediction of MRR and surface roughness of bevel gears finished by PECH.
- ✓ No work has been reported on specific energy consumption in ECH or PECH for finishing of gears.

- ✓ Most of the past work has been on finishing the cylindrical gears by ECH process and that too using constant power supply. Only two attempts have been made for the conical gears

Research Objectives: This is evident from the review of past work and research gaps that very limited work has been done on PECH process for improving the surface characteristics of the gears. Therefore, main goal of the present research work was to do high quality finishing of conical gears using PECH process focusing on simultaneous improvement in surface quality, surface integrity, wear characteristics (in terms of wear rate, frictional force, friction coefficient), and transmission characteristics. To accomplish this following research objectives identified:

- ❖ To modify and improve the finishing chamber available for conical gear finishing by ECH by rectifying its drawbacks and making it adaptable to PECH process.
- ❖ To automate the engagement and disengagement of the workpiece bevel gear with cathode and honing gears for better control and ease of operation.
- ❖ Design and planning of experimental investigations to meet the main goal.
- ❖ To study role of pulse power supply and other PECH parameters for finishing of straight bevel gears by studying its effects on the considered responses of the PECH finished gears.
- ❖ To study the effects of electrolyte parameters (i.e. composition, concentration and flow rate), applied voltage and rotary speed on the considered responses of the workpiece gear.
- ❖ To study role of honing gear hardness in improving surface characteristics of gears during PECH process.
- ❖ To develop theoretical models for volumetric MRR and surface roughness depth of straight bevel gears in PECH process and their experimental validation.
- ❖ To compare the process performance of PECH with PECF and with ECH for bevel gear finishing with an objectives to justify need hybridization of PECF with mechanical honing and to prove the usefulness of pulse power supply in ECH process.
- ❖ A comparative study on specific energy consumption for achieving same level of finishing through ECH and PECH.

Research Methodology: Fig. 2 presents the research methodology adopted in the present work to meet the identified research objectives.

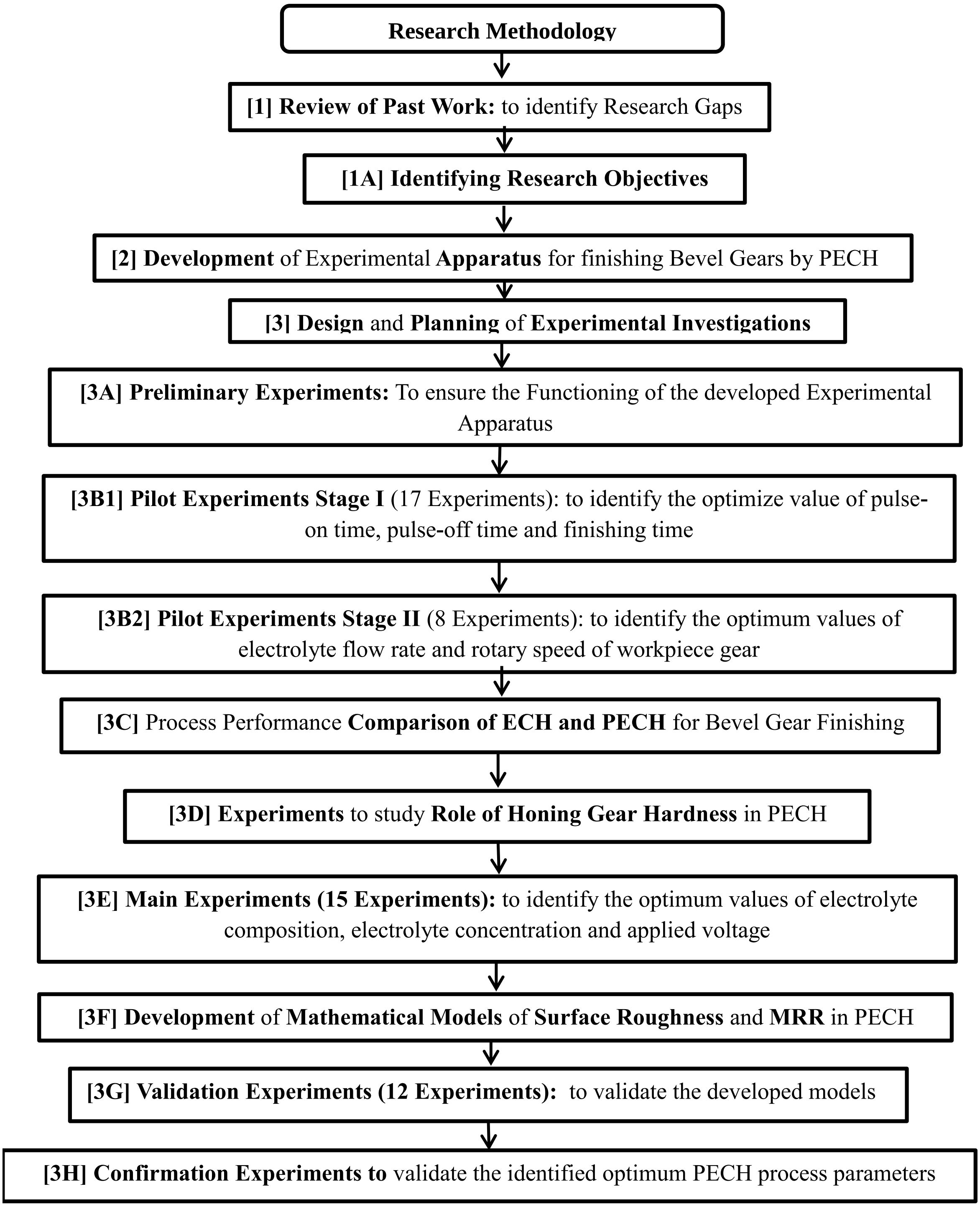
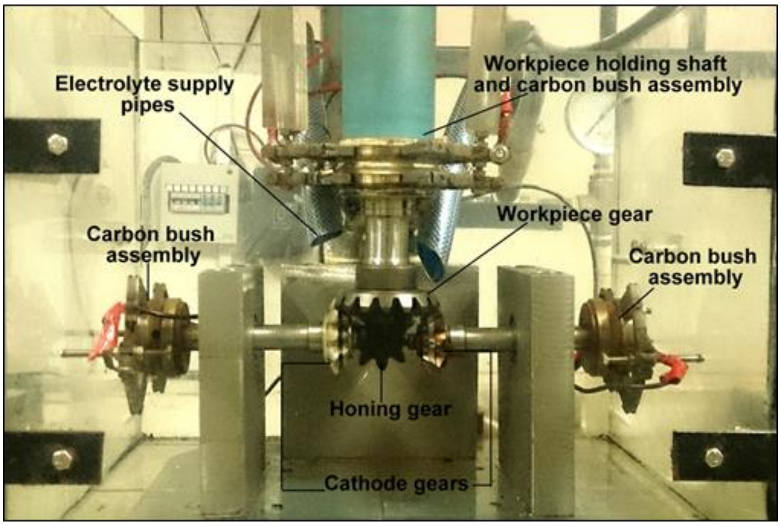


Fig. 2 Research methodology of the present research work

Brief Description of the Experimental Apparatus: Finishing of bevel gears by PECH is very difficult and challenging as compared to that of cylindrical gears due to their complex geometry which restricts the reciprocation of workpiece gear and inhibits the finishing of entire face width. This problem was solved by using the concept of twin complementary cathode gears as envisaged by **Shaikh (2014a)**. Same concept has been used in the present work for simultaneous finishing of full face width of all the teeth of the workpiece bevel gear. In this concept, one of the cathode gears has a conducting layer of copper sandwiched between two non-conducting layers of metalon while, other complimentary cathode gear has a non-conducting layer of metalon sandwiched between two conducting layers of copper. The conducting layers in both the complementary cathode gears are undercut by 1 mm than the insulating layers so as to avoid short-circuiting when these gears mesh with the workpiece gear while finishing it. This also ensures that IEG required for PECF is maintained between the workpiece and cathode gears.

Fig 3a depicts the designed and developed finishing chamber arrangement based on this concept. While, Fig. 3b depicts the photographs of the complementary cathode gears, workpiece bevel gear and honing gear. The developed experimental apparatus comprises of four major sub-sections as mentioned below:



(a)

(b)

Fig. 3 (a) Photograph of finishing chamber arrangement for bevel gear finishing by PECH and; (b) Photographs of workpiece bevel gear, honing gear and complementary cathode gears.

(a) Power Supply System: The *DC pulse power supply unit* used for the experimentation is capable of delivering an output voltage in the range of 0–100 V, current in the range of

10-110 A and it is equipped with the option for setting pulse-on time and pulse-off time. It comprises of three parts: programmable high-power DC supply, pulse generator and pulse controller with the power switch unit. The pulse controller has the facility to modify the voltage, current, pulse-on time (T_{on}), pulse-off time (T_{off}) and consequently the duty cycle (ζ) i.e. ratio of pulse-on time to sum of pulse-on and pulse-off times.

(b) Electrolyte supply and recirculating unit: The *electrolyte supply* and *recirculating unit* comprises of a pump to supply the desired quantity of the electrolyte to the finishing chamber at preset values of temperature and pressure. The system also includes pressure gauge, flow meter, flow control valves and filters. A heating element was fitted in the storage tank to maintain the electrolyte temperature at a prefixed value and it is controlled using a temperature controller and sensor. An aqueous solution of $NaNO_3$ and NaCl was used as electrolyte for anodic dissolution of workpiece gear material.

(c) Finishing chamber assembly: Fig. 3a shows photograph of the *finishing chamber* which consists of workpiece gear, two complementary cathode gears, honing gear and supporting and mounting elements for these gears. The workpiece bevel gear is mounted on the spindle of the vertical bench drilling machine, while the two complementary cathode gears and honing gear is mounted on a stainless steel block of same dimension and supported with the help of stainless steel shafts to avoid corrosion in the finishing zone. The workpiece gear simultaneously meshes with the specially designed cathode gears and honing gear which avoids short-circuiting and also maintains an IEG. The structure of the finishing chamber was made of perspex sheets due to its resistance to corrosion and to provide better visibility during the finishing operations. Finishing chamber is rested over the table of 400 mm X 400 mm dimension of the drill machine to avoid the vibration during the finishing action.

(d) Tool and Motion system: The *tool and motion unit* consists of a stepper motor, its driver and a controller programmed by software from *Copley Controls Corporation*. It provides reciprocating motion to the spindle of the bench drilling machine on which the workpiece gear is mounted. It makes the workpiece gear to engage with the honing and cathode gears before its finishing by PECH and disengages it after completion of the finishing operation. A high level of accuracy in feed and better control over process can be achieved using this automation in the feed operation. The rotary motion to the workpiece gear is provided by the DC motor attached to the spindle of the vertical drilling machine.

The workpiece gears and honing gear were made of case hardened 20MnCr5 alloy steel which is most commonly used bevel gear material for commercial applications. All the bevel gears were manufactured on *Gleason* principle based bevel gear manufacturing machine. The workpiece gear has 16 teeth while the cathode gears and honing gear have 10 teeth each, all the gears were made of same module i.e. 4.83 to ensure the proper meshing. The workpiece bevel gears are hardened up to the hardness value of 630 HV, whereas the honing gear is having slight higher hardness values i.e. up to 670 HV.

Experimentation: To meet the identified research objectives, experimental investigation was planned in different stages using the most appropriate design of experiments approach. Table 1 presents details of the fixed and variable parameters, considered responses and design of experiments approach used in different types of experiments.

In the first stage of pilot experiments seventeen experiments were planned and conducted by varying the pulse-on time (T_{on}), pulse-off time (T_{off}) and finishing time (t) each at five levels using *central composite design* (CCD) approach of response surface methodology (RSM) to identify their optimum values for further experiments. Eight experiments were conducted using "*D-Optimal technique*" of RSM in stage-II of pilot experiments by varying electrolyte flow rate 'F' at three levels and rotary speed 'R' of the workpiece gear at four levels to identify their optimum values for further investigations. To study the role of honing gear hardness in PECH two similar straight bevel gears were finished by PECH process to compare their surface quality and surface integrity by finishing them (i) using a honing gear of similar hardness as that of workpiece gear (i.e. 630 HV); and (ii) using a honing gear case hardened by plasma nitriding process and having hardness value of 900 HV. Fifteen experiments were performed using "*Box-Behnken approach*" of RSM to study the effects of three most important PECH parameters namely applied voltage, electrolyte composition and electrolyte concentration on various aspects of surface quality, surface integrity and finishing productivity of the straight bevel gears by varying them at three levels each. Twelve experiments were performed using one factor at one time approach to validate the developed mathematical models of MRR and depth of surface roughness varying pulse-on time, pulse-off time and applied voltage at 4 levels. Two experiments were performed to validate the optimum combination of input parameters obtained from the results of pilot experiments (stage-I and stage-II) and main experiments. A comparative study on process performance of PECH with PECF was also performed to justify need of hybridization of PECF with mechanical honing and comparing performance of PECH with ECH was done to prove the usefulness of pulsed-power in ECH process using results of (**Shaikh, 2013** and **Misra, 2014**).

Table 1: Details of experimental investigations for different stages.

Type of experiments	Process parameters		Considered responses
Pilot experiments (Stage I) [17 experiments using CCD approach]	**Variable parameters** **1.** Finishing time (*t*): 5 levels (3, 6, 9, 12, 15 min) **2.** Pulse-on time (T_{on}): 5 levels (1, 2, 3, 4, 5 ms) **3.** Pulse-off time (T_{off}): 5 levels (3, 4.5, 6, 7.5, 9 ms)	**Fixed parameters** **1.** Electrolyte concentration (*C*): 7.5 % (by wt.) **2.** Electrolyte temperature (*T*): 32^0 C **3.** Voltage (*V*): 12 Volts **4.** Electrolyte composition (*E*): 75% $NaNO_3$ + 25% NaCl **5.** Electrolyte flow rate (*F*): 30 lpm **6.** Rotary speed of workpiece gear (*R*): 40 rpm	**1.** Surface roughness **2.** Material ratio curve **3.** Wear indicators **4.** Micro-geometry **5.** Microstructure **6.** Micro-hardness
Pilot experiments (Stage II) [8 experiments using D-optimal design approach]	**Variable parameters** **1.** Electrolyte Flow rate (*F*): 3 Levels (10-20-30 Lpm) **2.** Rotary speed of workpiece gear (R):4 Levels (20-30-40-60 RPM)	**Fixed parameters** **1.** Voltage (V): 12 Volts **2.** Pulse-on time (T_{on}): 2 ms **3.** Pulse-off time (T_{off}): 4.5 ms **4.** Finishing time (*t*): 6 minutes **5.** Electrolyte concentration (R): 7.5 % (by wt.) **6.** Electrolyte temperature (*T*): 32^OC **7.** Electrolyte composition (*E*):75% $NaNO_3$ + 25% NaCl	**1.** Surface roughness **2.** Micro-geometry **3.** Surface topology **4.** Microstructure **5.** Micro-hardness
Experiments to study the role of honing gear hardness [2 experiments]	**Variable parameters** 1. Hardness of the honing gear a. Unhardened: 630 HV b. Hardened by plasma nitriding process: 900HV	**Fixed parameters** Parameters optimized from stage I and stage II of the pilot experiments	**1.** Surface roughness **2.** Micro-geometry **3.** Flank topology **4.** Microstructure ***5.*** Micro-hardness
Main Experiments [15 experiments using BBD approach]	**Variable parameters** **1.** Electrolyte Composition (*E*): 3 levels (75% $NaNO_3$ + 25% NaCl; 50% $NaNO_3$ + 50% NaCl and 25% $NaNO_3$ + 75% NaCl) **2.** Electrolyte concentration (C) 3 levels (5, 7.5 and 10%) (by wt.) **3.** Voltage (*V*): 3 levels (8; 12 and 16 Volts	**Fixed parameters** **1.** Pulse-on time(T_{on}):: 2 ms **2.** Pulse-off time(T_{off}):: 4.5 ms **3.** Finishing time(*t*): 6 minutes **4.** Electrolyte temperature (*T*): 320C **5.** Electrolyte flow rate (*F*): 20 lpm ***6.*** Rotary speed (R): 40 RPM	**1.** Surface roughness **2.** Material ratio curve **3.** Volumetric MRR **4.** Wear indicators **5.** Micro-geometry **6.** Flank topology **7.** Microstructure **8.** Micro-hardness **9.** Residual stresses
Confirmation experiment and Process performance comparison of PECH with PECF [2 experiments]	**----**	Optimum values identified from pilot experiments (Stage I and II) and Main Experiments	**1.** Surface roughness **2.** Volumetric MRR **3.** Micro-geometry **4.** Microstructure **5.** Micro-hardness
Experiments to validate the theoretical models of surface roughness and MRR	**Variable parameters** **1.** Voltage (*V*): 4 levels (8-12-16-20) Volts **2.** Pulse-on time (T_{on}): 4 levels (2-3-4-5) ms **3.** Pulse-off time (T_{off}): 4 levels (2-4-6-8) ms	**Fixed parameters** **1.** Electrolyte composition (*E*): 25% $NaNO_3$ +75% NaCl **2.** Electrolyte temperature (*T*): 32^0C **3.** Electrolyte flow rate (*F*): 20 Lpm **4.** Rotary speed (*R*): 40 RPM **5.** Electrolyte concentration (*C*): 7.5 % (by wt.) **6.** Finishing time (*t*): 6 minute	**1**. Volumetric MRR **2**. Depth of surface roughness

Responses and their Measurement: 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 contour-cum-tracing equipment from *Kosaka, Japan* for pilot and other experiments and using the *3D surface roughness and gear tooth flank topology machine LD 130* from *Mahr Metrology Germany* for the main experiments, theoretical model validation experiments and confirmation experiments. All the measurements used filtering length of 0.25 mm and assessed length of 1.6 mm. Three measurements were taken on different locations along the pitch line on left hand and right hand flanks of two consecutive gear teeth. Arithmetic average values 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 change in that surface roughness parameter i.e. average percentage improvement in average surface roughness value 'PIR_a' can be calculated by Eq. 1.

$$Avg.\ PIR_a = \frac{Avg.\ R_a\ value\ of\ an\ unfinished\ gear - Avg. R_a\ value\ of\ the\ PECH\ finishined\ gear}{Avg. R_a\ value\ of\ the\ unfinished\ gear} \quad (1)$$

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 measured values. A higher value of percentage change in a concerned parameter of roughness implies lower value of that parameter after finishing by the PECH process. Material ratio curve, average and maximum waviness were also evaluated using the same filtering length and assessed length. Average value of volumetric MRR was calculated by dividing the weight 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. 2). Weight of the workpiece gear before and after finishing was measured on a precision weighing balance (make *Essae-Teraoka Ltd.*) having a least count of 10 mg.

$$Avg. MRR = \frac{weight\ of\ unfinished\ gear\ (gm) - weight\ of\ PECH\ finished\ gear\ (gm)}{Finishing\ time\ (s)\ x\ Density\ of\ the\ workpiece\ material\ (gm/mm^3)} (mm^3/s) \quad (2)$$

Wear indicators, micro-hardness, microstructure and residual stresses were studied for the unfinished gear and the best finished gear by PECH using the identified optimum values of the PECH parameters. Wear tests were conducted to evaluate the coefficient of sliding friction and friction force using fretting wear tribometer (model CM-9104) from *Ducom, India* using 5 mm ball diameter; load of 50 N; frequency of 20 Hz; and for duration of 20 minutes. Vicker's micro-hardness was measured using a load of 0.5 kg and dwell time of 15 seconds on the micro-hardness tester (model VMH-002) from *Walter UHL, Germany*. Changes in the microstructure of the gear tooth flank surface before and after finishing by PECH were studied through scanning electron microscopic (SEM) images obtained by FE-SEM (model *Supra 55*) from *Carl Zeiss, Germany*. Residual stresses were measured on X-ray diffractometer (model *Stress X-3000*) from *Ital Structure, Italy* using a mixture of argon and methane gas in the ratio of 9:1; gas pressure of 7.5 bar and voltage of 30 kV.

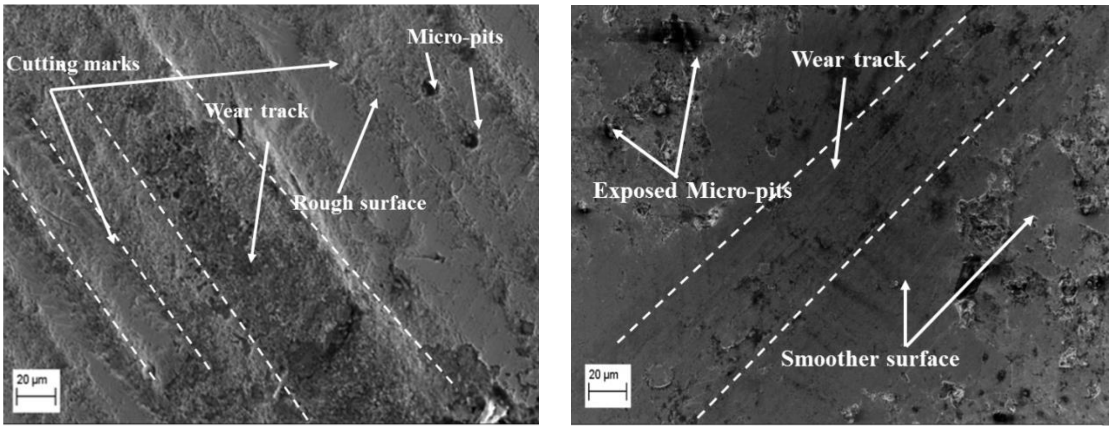
Four parameters of micro-geometry [i.e. single pitch error (f_p), adjacent pitch error (f_u), cumulative pitch error (F_p), and total runout (F_r)] and tooth flank topology were measured before and after finishing by PECH using a CNC gear metrology machine ***SmartGear 500*** from ***Wenzel GearTec, Germany***. For each experiment, the measurement were taken on left hand (LH) and right hand (RH) flanks of all the 16 teeth of a gear before and after its finishing by PECH. The average values of f_p, f_u and F_p before and after finishing by PECH were calculated by taking the arithmetic mean of their corresponding values on LH and RH flanks. The average value of percentage improvement in the single pitch error 'f_p' values (PIf_p) was calculated using the Eq. (3).

$$Avg.PIf_p = \frac{Avg.f_p\ value\ of\ an\ unfinishjed\ gear - Avg.f_p\ value\ of\ the\ PECH\ finished\ gear}{Avg.f_p\ value\ of\ the\ unfinishjed\ gear} \quad (3)$$

Similarly, average percentage improvement in adjacent pitch error (PIf_u) and average percentage improvement in cumulative pitch error (PIF_p) were calculated. Values of total runout before and after finishing by PECH were used to calculate percentage improvement in the runout (PIF_r). Higher value of percentage improvement in a micro-geometry parameter indicates smaller values of that parameter after finishing bevel gear by PECH.

Results and Brief Discussion

(a) Results of Pilot Experiments: From the pilot experiments it was observed that the best combination of average percentage improvements in surface finish and micro-geometry of the PECH finished bevel gears was achieved for the parametric combination of T_{on} as 2 ms; T_{off} as 4.5 ms and finishing time as 6 minutes. It yielded average values of percentage improvements in single pitch error (PIf_p), adjacent pitch error (PIf_u), cumulative pitch error (PIF_p) and total runout (PIF_r) equal to 34.2%; 39.6%; 13.3% and 18.9% respectively. Simultaneously, it also resulted in the best improvements in average percentage improvements in average surface roughness (PIR_a), maximum surface roughness (PIR_{max}) and depth of surface roughness (PIR_z) equal to 47.3%; 46.2%; and 34.2% respectively. Material ratio curve (MRC) of the best finished gear resulted in larger contact area which will give better contact ratio, enhanced transmission accuracy and reduced wear rate which in turn yield better service life of bevel gears. Measurement of wear characteristics of the best finished gear on fretting wear machine revealed that the coefficient of sliding friction reduced from 0.157 to 0.046 causing reduction in friction force from 7.5 to 1.4 N due to the reduction in the surface roughness of the gear tooth flank after finishing by PECH. Fig. 4 depicts SEM images showing the microstructure taken after the wear tests, for the unfinished gear (Fig. 4a) and the best finished gear by PECH (Fig. 4b) using the identified optimum input parameters. It can be seen from these images that PECH smoothens the tooth flank surfaces. This will lead to less material is being worn out from tooth flank surfaces. Optimum values of electrolyte flow rate and rotary speed of the workpiece gear were identified as 20 liters per minute (lpm) and 40 rpm during stage-II of the pilot experiment. This combination yielded the best combination of simultaneous improvements in considered parameters of surface roughness, micro-geometry and tooth flank topology.



(a) (b)

Fig. 4 SEM images (at 500X magnification) showing microstructure of the gear tooth after wear test for (a) an unfinished gear; and (b) for the best finished gear by PECH using the optimum input parameters identified during stage-I of the pilot experiments.

(b) Role of Honing Gear Hardness in PECH: Effects of honing gear hardness were studied by finishing two similar straight bevel gears by PECH process: one gear was finished using a honing gear of similar hardness as that of workpiece gear (i.e. 630 HV) while the other gear was finished using the honing gear which was case hardened by plasma nitriding process and having hardness value of 900 HV. Identified optimum values of all other PECH parameters were used during finishing of both the gears and comparative analysis was done on the basis of their surface roughness, micro-geometry and tooth flank topology. The results of this study revealed that the maximum surface roughness of the bevel gear finished using the plasma nitrided hardened honing gear improved by more than 50% and tooth flank topology became more uniform than that finished using an unhardened honing gear. Improvement in flank topology will avoid poor tooth contact and help in proper meshing of the gear thus helping in reduction in transmission errors and running noise. It also established that use of hardened honing gear improves micro-hardness of the bevel gear which results in better wear resistance thus improving working life and reducing the uncertain premature failures of bevel gears during their use. Role of honing gear in PECH can be better understood with help of the sequence of mechanism as described in Fig. 5. It can be observed from this figure that during the electrolytic dissolution of the workpiece gear, a metallic oxide passivation layer is formed on its teeth flank surfaces prohibiting further electrolytic dissolution from these surfaces. Use of an unhardened honing gear removes a very small amount of material from some of the highest peaks of these surfaces while scrubbing the passivation layer. Whereas, use of a hardened honing gear (i.e. having 30 % more harder than the workpiece gear) removes material from almost all the peaks of these surfaces. This leads to comparatively more reduction in maximum surface roughness which also helps subsequent electrolytic dissolution to remove some material even from the valleys imparting better and uniform surface finish, micro-geometry and tooth flank topology. Therefore, it can be concluded that hardness of the honing gear can also be used as one parameter in improving surface characteristics of the PECH finished gear.

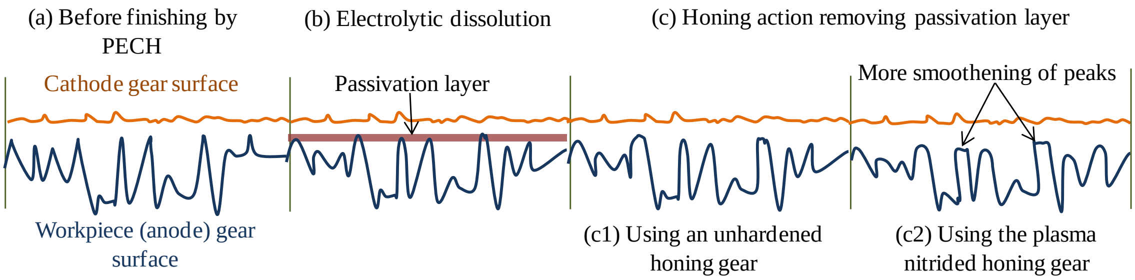
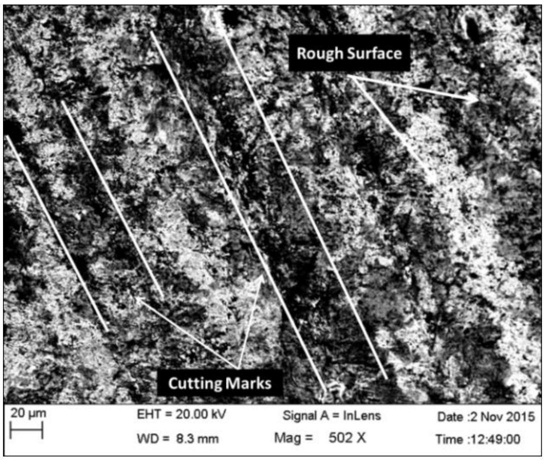
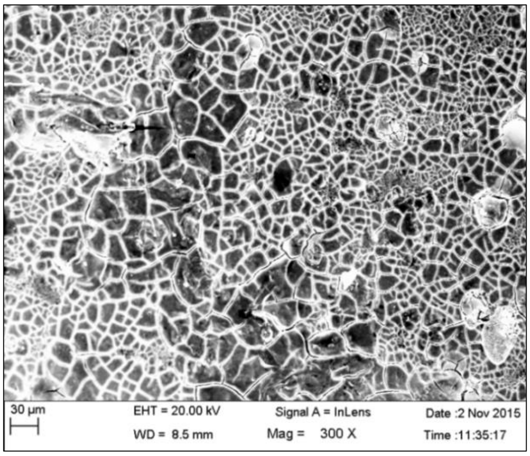


Fig. 5 Sequence of finishing the bevel gear by PECH process; (a) before finishing by PECH; (b) after electrolytic dissolution and formation of metallic oxide passivation layer; (c1) after honing action using an unhardened honing gear; and (c2) after honing action using the plasma nitrided honing gear.

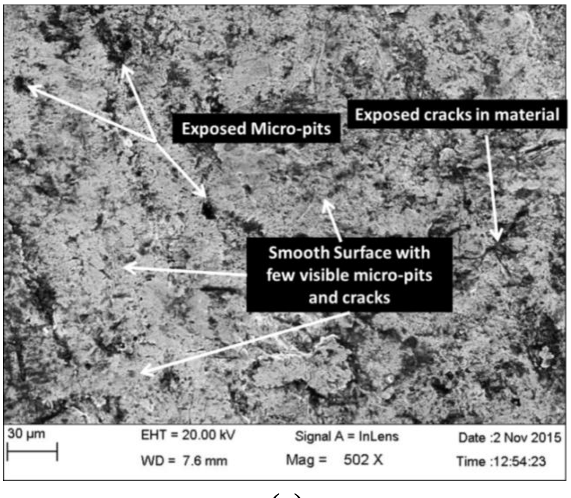
(c) Results of Main Experiments: From the results of main experiments, the best combination of considered responses (i.e. surface finish, waviness, material ratio curve, micro-geometry, wear indicating parameters, tooth flank topology, microstructure, residual stresses and micro-hardness) was obtained for parametric combination of 75 wt. % NaCl + 25 wt. % $NaNO_3$ as electrolyte composition; 7.5 wt. % as electrolyte concentration; and 8 volts as applied voltage. Figure 6 presents the SEM images showing microstructure of the unfinished gear (Fig. 6a) and the best finished gear (Fig. 6c) by PECH using the identified optimum parameters. It can be seen in Fig. 6a that an unfinished gear tooth surface has deep cutting marks, scratches and rough surface with high peaks all over the scanned area. The SEM image of Fig. 6b depicts the formation of passivation layer during the PECF which restricts the further finishing action if it is not scrubbed properly thus leading to poor surface finish. Due to the use of passivating electrolyte $NaNO_3$, formation of the passivation layer is so strong that it is not easy for the electrolyte flow to scrub it. It can be observed in Fig. 6c that the hardened honing gear removed passivation layer more effectively helping in smoothening of the gear tooth flank surface after removal of cutting marks, scratches and deep grooves by PECH process. Effective removal of the passivation layer helps in continuation of the finishing action by PECF which further smoothen the gear flank surfaces having lower values of roughness and waviness parameters. This will improve wear resistance and service life of bevel gears.



(a)



(b)



(c)

Fig. 6 SEM images (at 500X magnification) showing microstructure of the gear tooth flank surface of (a) an unfinished gear; and (b) gear tooth flank having passivation layer; and (c) the best finished gear by PECH using the optimum parameters identified during the main experiments.

(d) Comparison of Performance of PECH with PECF and with ECH: A comparative study of process performance of PECH with ECH for bevel gear finishing was done so as to justify the use of pulse power supply in enhancing the working performance, transmission efficiency and service life of the bevel gears. This comparison was done using the results of the present work for the best finished bevel gear in stage I of pilot experiments (i.e. using identified optimum values of pulse-on time, pulse-off time and finishing time) with the corresponding best results obtained by **Shaikh *et al.* (2013)** and **Misra *et al.* (2014)**. Process performance was compared in terms of percentage improvement achieved in the parameters of micro-geometry and surface roughness of tooth flank surfaces of the straight bevel gears. This study proves that use of pulse power supply in PECH may reduce its productivity but strongly helps in achieving simultaneous improvements in the parameters of surface roughness and micro-geometry by significant amount thus enhancing their service life and working performance. Improvements obtained in parameters of micro-geometry [i.e. pitch error and runout] of the PECH-finished gears are more than 50% as compared to the ECH-finished gears obtained by **Shaikh *et al.* (2013)**.

Investigation was also done to compare process performance of PECH with PECF in terms of considered parameters of surface quality, surface integrity and finishing productivity with an objective to justify need of the hybridization of PECF with mechanical honing by (i) finishing one workpiece bevel gear by PECH process; and (ii) finishing the similar workpiece gear by PECF process i.e. using only complementary cathode gears and no honing gear. Both experiments used the optimum values of the PECH parameters identified from the pilot and main experiments. This study proves that PECH helps in achieving simultaneous improvements in the parameters of surface roughness, micro-geometry and finishing productivity by significant amount. Improvements obtained in considered responses are more than 50% as compared to those achieved by PECF process.

(e) Comparative Study of Specific Energy Consumption: Study was done to compare the consumption of specific energy in PECH and ECH processes for achieving similar level of finishing by them. Equations (4) and (5) were used to compute specific energy consumption by PECH and ECH respectively assuming that both ECH and PECH processes consume the same power (i) to rotate the workpiece gear; (ii) to pump the electrolyte; (iii) to maintain electrolyte temperature higher than the ambient temperature.

$$Specific\ energy\ consumption\ in\ PECH;\ E_{PECH} = \frac{V\ I\ t\ \delta}{\eta_m MRR} \quad \left[\frac{J}{mm^3/s}\right] \quad (4)$$

$$Specific\ energy\ consumption\ in\ ECH;\ E_{ECH} = \frac{V\ I\ t}{\eta_m MRR} \quad \left[\frac{J}{mm^3/s}\right] \quad (5)$$

Here, V is applied voltage, I is current; t is finishing time, δ is duty cycle (i.e. ratio of pulse-on time to the sum of pulse-on time and the pulse-off time $i.e. \delta = \frac{T_{on}}{T_{on}+T_{off}}$*); and* η_m *is the efficiency of the machine. The efficiency of the experimental apparatus (can be assumed as 50 % for both ECH and PECH).*

It was found from comparison of specific energy consumption computed from the results of the main experiments that PECH achieved maximum value of avg. PIR_{max} of 36.4% with specific energy consumption of 47.5 KJ/mm^3/s whereas, ECH consumes 62.7 KJ/mm^3/s to achieve maximum value of 32.2% of avg. PIR_{max} i.e. 25% less specific power consumption. Thus, it can be concluded that the use of pulse-power in PECH process helps in reducing the specific energy consumption making it more energy-efficient than ECH process.

(f) Modeling of MRR and Depth of Surface Roughness in PECH Process: Since, PECH is hybrid finishing process combining working principle and advantages of PECF and mechanical honing therefore development of model of volumetric MRR and surface roughness depth 'R_z' in PECH process should be based on the contribution of these two constituent processes. In the present work, contribution of PECF has been modeled using the fundamental equations derived from the faraday's law of electrolysis. While, contribution of mechanical honing has been modeled considering the material removal by honing as a process of uniform wear whose formula is given by **Archard (1953)**. Following assumptions have been made in developing the mathematical model for MRR and roughness depth in PECH process:

(i) Inter electrode gap (IEG) and electrolyte conductivity remain constant during finishing of gears by PECH.

(ii) Electrical conductivity of the anode (i.e. workpiece gear) and cathode gear is very large as compared to that of the conductivity of the electrolyte.

(iii) The line passing through the end points of the involute profile is parallel to the line tangent to the tooth profile at the pitch point.

(iv) Material removal by PECF action takes place during pulse-on time only and only from the flank surfaces and top land of the workpiece bevel gear because no material is removed from bottom land and root fillet due to very high value of IEG at these locations as compared to flank surfaces and top land and non-removal of the passivating layer of metal oxide from these surfaces of a bevel gear during the honing action.

(v) Some fraction of the pulse-on time (which is referred as rise time) is consumed in attaining the final desired value of DC voltage and no electrolytic dissolution of anodic workpiece gear takes in this duration of pulse-on time.

(vi) **Archard's** (1953) law of uniform wear has been used to compute the material removed by mechanical honing action from flank surfaces of the workpiece gear by a hard or hardened honing gear.

(vii) Contribution of electrolytic dissolution and mechanical honing in total material removed by PECH process is multiplied by their respective contribution factors (having values less than one) to take into account their hybridization. Literature has mentioned values of the contribution factors in the range of 0.8-0.9 for electrolytic dissolution and 0.1-0.2 for mechanical honing.

$$\text{Volumetric MRR in PECH process, } V_{PECH} = C_{PECF} V_{PECF} + C_h V_h \tag{6}$$

Following expressions were obtained for volumetric MRR (i.e. V_{PECH}) and depth of surface roughness in PECH ($R_{(z)PECH}$) process after making required corrections to the theoretical models developed by **Shaikh and Jain (2014)** keeping in view the process mechanism of PECH and in accordance with the assumptions made in the present work:

$$V_{PECH} = \left[\frac{C_{PECF}\ \eta E_w K_e A_s(1-\lambda)}{F\rho_w Y}\right](\boldsymbol{V}-\Delta V)\frac{\boldsymbol{T_{on}}}{\boldsymbol{T_{on}}+\boldsymbol{T_{off}}} + \left[\frac{2C_h K F_n L_{iw} T}{H}\right]\boldsymbol{N_s} \quad \left(\frac{mm^3}{s}\right) \tag{7}$$

$$R_{Z_{PECH}} = R_{Zi} - 10^{-3}(1-2k)f\left[\frac{C_{PECF}\eta E_w K_e(1-\lambda)}{F\rho_w Y}(\boldsymbol{V}-\Delta V)\frac{\boldsymbol{T_{on}}}{\boldsymbol{T_{on}}+\boldsymbol{T_{off}}}\boldsymbol{t} + \frac{2C_h K F_n\ L_{iw}\ T}{A_f H}\boldsymbol{N_s t}\right] (\mu m) \tag{8}$$

In which; $\boldsymbol{A_s}$ *is the effective surface area of the workpiece bevel gear tooth from which material is removed by PECF process (mm^2);A_f: Area of workpiece bevel gear tooth flank surface; C_{PECF}: Contribution factor for PECF; C_h: Contribution factor for mechanical honing; D_w: Working depth of the workpiece bevel gear; E_w: Electrochemical equivalent of the workpiece material (g); F: Faraday's constant (=96,500 C); F_n: Total normal load acting along the line of action (N); f: Factor used to convert the height of rectangle into height of a triangle with same area and the base length (=2); H: Brinell hardness number (BHN) of the workpiece material (N/mm^2) K: Wear coefficient; K_e: Electrical conductivity of the electrolyte (Ω^{-1}mm^{-1}); k: Factor that indicates proportion of total thickness of material removed from the valleys in one cycle of PECF and honing (=0.45); L_{iw}: Length of the involute arc of the workpiece bevel gear tooth flank (mm); N_s: Number of revolutions of the workpiece gear per second (rps); R_{Zi}: Depth of surface roughness of an unfinished gear flank surface (μm); T: Number of teeth on the workpiece gear; T_{on}: Pulse-on time; T_{off}: Pulse-off time; t: Finishing time (s); V: Applied voltage (volts); ΔV: Over voltage* *(volts); Y: Inter-electrode gap (mm); ρ_w: Density of the workpiece gear material (g/mm^3); η: Current efficiency; λ:* Percentage of pulse-on time to attain the final value of the applied voltage i.e.$\left(\boldsymbol{\lambda} = \frac{\boldsymbol{t^*}}{\boldsymbol{T_{on}}}\right)$.

Major Conclusions

- ✓ Identification of the optimum combination of different PECH parameters 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 for simultaneous improvement in surface quality and micro-geometry parameters i.e. average surface roughness as 62.45 %; maximum surface roughness as 60.58 %; depth of surface roughness as 53.98 %; single pitch error as 36.0 %; adjacent pitch error as 57.1 %; cumulative pitch error as 23.5 %; total runout as 34.6 %.
- ✓ Significant improvement in quality of PECH-finished bevel gear i.e. DIN standard improved from DIN 10 to DIN 7.
- ✓ Excellent improvements in microstructure of PECH-finished bevel gears.
- ✓ Significant improvements in surface integrity aspects of the PECH-finished bevel gears (i) wear indicators as coefficient of sliding friction reduced to 0.04 from 0.157 reducing friction force to 1.5 N from 7.8 N; (ii) Micro-hardness of PECH finished gears improved from 630-640 HV to 713-730 HV and compressive residual stresses increased from 378 MPa to 421 MPa.
- ✓ Role of honing gear hardness: Present work finds a new and important parameter of PECH i.e. hardness of honing gear. It was observed that honing gear with higher hardness value than workpiece gear also plays crucial role in material removal mechanism and provides better surface finish and micro-geometry as compared to gear finished using unhardened honing gear.
- ✓ Sustainability of PECH: present work reveals that PECH is sustainable and energy-efficient process as compared to the ECH process.
- ✓ Material removal mechanism and modeling: present work also describes the mechanism of generation of passivation layer and role of honing gear in removing it, which helps in better understanding of hybridization of PECF and mechanical honing.

- ➢ Theoretical models have been developed for prediction of MRR and depth of surface roughness of bevel gears finished by PECH. The developed models have shown very good prediction accuracy and correctly capturing the process response.

List of Publications of Sunil Pathak

[A] Book Chapters [3]

1. Neelesh Kumar Jain, **Sunil Pathak (2016)**, **“Chapter 30028: “**Electrochemical Processing and Surface Finish” in **Comprehensive Materials Finishing Vol. 3** (Volume Editor: Bakir Sami Yilbas; Editor-in-Chief: S. Hashmi) Elsevier Inc. Oxford (UK). (DOI: 10.1016/B978-0-12-803581-8.09182-7; online since 29 April 2016). (ISBN: 978-0-12-803581-8)

2. Neelesh Kumar Jain**, Sunil Pathak (2016)**, “Fine Finishing of Gears by Electrochemical Honing Process” in **Nanofinishing Science and Technology: Basic and Advanced Finishing and Polishing Processes** (Editor: V K Jain), CRC Press, Taylor and Francis, New York (USA).

3. **Pathak, S.;** Jain, N. K. & Palani, I A **(2014)**, “Improving Surface Quality of Bevel Gears by Pulsed-ECH Process” Chapter 19 in **DAAAM International Scientific Book 2014**, pp. 221-238, B. Katalinic (Ed.), Published by *DAAAM International* Vienna, Austria, ISBN 978-3-901509-94-0, ISSN 1726-9687. (DOI: 10.2507/daaam.scibook.2014.19)

[B] Papers in Refereed International Journals

[B.1] From the PhD thesis work [7]

4. **Sunil Pathak**, N. K. Jain, I. A. Palani **(2016)** “Effect of Applied Voltage and Electrolyte Parameters on Pitch, Runout, Flank Topology and Finishing Productivity of the Straight Bevel Gears in PECH Process” **Materials and Manufacturing Processes,** DOI: 10.1080/10426914.2016.1198022 (online since July 2016) (**Impact Factor: 1.63**).

5. **Sunil Pathak**, N. K. Jain, I. A. Palani **(2016)** “Investigations on Surface Quality, Surface Integrity and Specific Energy Consumption in Finishing of Straight Bevel Gears by PECH Process” **International Journal of Advanced Manufacturing Technology,** 85(9), 2207-2222 (July 2016) (DOI: 10.1007/s00170-016-8876-x) (**Impact factor: 1.57**).

6. **Sunil Pathak**, N. K. Jain, I. A. Palani **(2016), “**Effect of honing gear hardness on surface quality and micro-geometry improvement of straight bevel gears in PECH process” **International Journal of Advanced Manufacturing Technology,** 85(9)**,** 2197-2205, (July 2016) (DOI: 10.1007/s00170-015-7596-y) (**Impact factor: 1.57**)

7. **Sunil Pathak**, N. K. Jain, I. A. Palani **(2016) “**Experimental investigations on redefining the surface quality of bevel gears by pulsed-ECH” **Transaction of Institute of Metal Finishing**. 94(2), 64-69 (April 2016), (**Impact factor: 0.852**).

8. **Sunil Pathak**, N. K. Jain, I. A. Palani **(2015)**, "On Surface Quality and Wear Resistance of Straight Bevel Gears Finished by Pulsed Electrochemical Honing Process" **International Journal of Electrochemical Science,** 10(11), 8869-8885, Nov. 2015. (**Impact factor: 1.50**)

9. **Sunil Pathak**, N. K. Jain, I. A. Palani **(2015)**, "Process Performance Comparison of ECH and PECH for Quality Enhancement of Bevel Gears" **Materials and Manufacturing Processes,** 30(7), 836-841, July 2015. (**Impact factor: 1.63**).

10. **Sunil Pathak**, N. K. Jain, I. A. Palani **(2014)**, "On Use of Pulsed Electrochemical Honing to Improve Micro-geometry of Bevel Gears" **Materials and Manufacturing Processes** 29(11-12) 1461-1469, Nov. 2014. (**Impact factor: 1.63**).

[B.2] Other Journal Publications [3]

11. N. K. Jain, A Potpelwar, **Sunil Pathak**, N. K. Mehta **(2015)** "Iinvestigations on Geometry and Productivity of Micro-holes in Incoloy 800 by Pulsed Electrolytic Jet Drilling" **International Journal of Advanced Manufacturing Technology,** 85(9), 2083-2095 (July 2016) (DOI: 10.1007/s00170-016-8342-9) **(Impact Factor: 1.57)**

12. J. H. Shaikh, N. K. Jain**, Sunil Pathak (2015)**, "Investigations on Surface Quality Improvement of Straight Bevel Gears by Electrochemical Honing Process" **Proceedings IMechE, Part B: Journal of Engineering Manufacture** 230(7) 1242–1253 (July 2016) (DOI: 10.1177/0954405415584899) (**Impact Factor: 0.954**).

13. J. H. Shaikh, N. K. Jain, **Sunil Pathak (2015)**, "Performance Enhancement of Electrochemical Honing Process Using ANN Approach for Bevel Gear Finishing" **International Journal of Precision Technology,** 5(2), 157-169.

[B.3] Under Review [2]

14. **Sunil Pathak**, N. K. Jain **(2016)** "Modeling and Experimental Validation of Volumetric Material Removal Rate and Surface Roughness Depth of Straight Bevel Gears in Pulsed-ECH Process" submitted to **International Journal of Advanced Manufacturing Technology** on 14 June 2016 (Manuscript ID: JAMT-D-16-01925) (Impact factor: 1.46)**.**
15. **Sunil Pathak**, N. K. Jain **(2016)** "Critical Review of Electrochemical Honing: Sustainable and Alternative Gear Finishing Process" submitted to **Transactions of the IMF: The International Journal of Surface Engineering and Coatings** in May 2016 (Manuscript ID: DM-1102) (Impact factor: 0.95).

[C] Papers published in the Refereed Conference Proceedings [3]

16. **Sunil Pathak**, N. K. Jain, I. A. Palani (2016), "Study on Surface Imperfections of Gears: Sources, Effects and Techniques for Concerned Improvements" Proceedings of **30th International Conference on Surface Modification Technologies (SMT 30)** to be held in Milan, Italy during 29th June to 1st July 2016.
17. **Sunil Pathak**, N. K. Jain, I. A. Palani **(2015)**, "Influence of Electrolyte Flow Rate and Rotary Speed on Surface Modification of Bevel Gear Finished by PECH" Proceedings of **29th International Conference on Surface Modification Technologies,** June 10-12, 2015, Technical University of Denmark**, Copenhagen,** pp 112-118, Valardocs India, ISBN: 978-81-926196-2-0 (Editors: Dr. T. S. Sudarshan and Prof. M.A.J. Somers).
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CONTENTS

Item	Page No.
List of Figures ……………………………………………………………..	**xxxvii**
List of Tables ……………………………………………………………	**xlv**
Nomenclature …………………………………………………………...	**xlvii**
Abbreviations …………………………………………………………...	**xlix**
Chapter 1: Introduction …………………………………………….	**1-28**
1.1 Introduction to Gears …………………………………………….	1
1.2 Performance Characteristics of Gears ………………………...	2
1.2.1 Surface Quality of Gears	3
1.2.1.1 Surface Roughness ……………………………………….	3
1.2.1.2 Micro-geometry ………………………………………..	5
1.2.1.3 Gear Tooth Flank Topology ………………………….....	10
1.2.1.4 Wear Characteristics …………………………………..	10
1.2.2 Surface Integrity ……………………………………………….	10
1.2.2.1 Microstructure …………………………………………	11
1.2.2.2 Micro-hardness ………………………………………....	12
1.2.2.3 Residual Stresses ………………………………………	12
1.3 Materials, Manufacturing Processes and Standards for Gears ..	12
1.4 Conventional Finishing Processes for Gears ………………….	14
1.4.1 Gear Shaving ……………………………………………	17
1.4.2 Gear Burnishing …………………………………….......	18
1.4.3 Gear Honing ………………………………………………..	18
1.4.4 Gear Lapping …………………………………………….	20
1.4.5 Gear Grinding ……………………………………………	20
1.4.6 Summary of Limitations of Conventional Processes ……	22
1.5 Concept of Gear Finishing by ECH/PECH …………………...	22

1.5.1 Finishing of Cylindrical Gears 24
1.5.2 Finishing of Conical Gears 25
1.5.3 Process Parameters 26
1.5.4 Advantages 27
1.5.5 Limitations 28
1.6 Organization of the Thesis 28
Chapter 2: Review of the Past Work and Research Objectives .. 29-36
2.1 Past Work on Finishing Gears by ECF based Processes 29
2.2 Past Work on Finishing Gears by ECH and PECH Process 30
2.3 Identified Research Gaps 34
2.4 Research Objectives of the Present Work 34
2.5 Research Methodology 35
Chapter 3: Fabrication of the Experimental Apparatus 37-50
3.1 Details of the Experimental Apparatus 38
3.2 Subsystems of the Experimental Apparatus 39
3.2.1 Finishing Chamber and its Fabrication 39
3.2.2 Supporting Structure 41
3.2.3 Power Supply System 41
3.2.4 Electrolyte Supply and Recirculating System 43
3.2.5 Motion Providing System 46
3.3 Details and Fabrication of Cathode Gears 46
3.4 Details of Workpiece and Honing Gears 48
Chapter 4: Design and Plan of Experimental Investigations 51-66
4.1 Introduction to Design of Experiments 51
4.2 Response Surface Methodology (RSM) 55
4.2.1 Central Composite Design 56
4.2.2 Box-Behnken Design 57
4.2.3 Optimality Criterion Based Experimental Designs 58

4.3 Details of the Experimental Investigations ………………….. 59
4.3.1 Pilot Experiments ………………………….................. 60
4.3.1.1 Pilot Experiments (Stage I) ……………………... 60
4.3.1.2 Pilot Experiments (Stage II) ………………………. 61
4.3.2 Experiments to Study Role of Honing Gear Hardness ….. 61
4.3.3 Main Experiments ……………………………………. 61
4.3.4 Confirmation Experiments ……………………………… 61
4.3.5 Comparison of Process Performance of PECH with PECF and ECH 62
4.3.6 Experiments to Validate Theoretical Models …………..... 62
4.4 Evaluation of Responses ……………………………………. 62
4.4.1 Evaluation of the Surface Quality...................................... 62
4.4.1.1 Evaluation of Surface Finish, Waviness and Material Ratio Curve ………... 62
4.4.1.2 Measurement of Wear Indicating Parameters ……….. 63
4.4.1.3 Evaluation of Micro-geometry ………………………... 63
4.4.1.4 Evaluation of Gear Tooth Flank Topology ...……......... 64
4.4.2 Characterization of Surface Integrity ………………………... 64
4.4.2.1 Evaluation of Microstructure ………………………….. 64
4.4.2.2 Measurement of Micro-hardness ………………………. 64
4.4.2.3 Measurement of Residual Stresses ……………………. 64
4.4.3 Evaluation of Productivity of PECH Process ……………….. 64
4.5 Procedure of Experimentation ………………………………… 65
Chapter 5: Results and Analyses ………………………………… 67-124
5.1 Results and Analysis of Stage-I of Pilot Experiments ……….. 67
5.1.1 Effect of Pulse-on Time, Pulse-off Time and Finishing Time on Surface Roughness and Micro-geometry……. 69
5.1.2 Analysis of the Best Finished Gear ………………………. 74
5.1.2.1 Surface Roughness and Material Ratio Curve ………. 74

5.1.2.2 Micro-geometry …………………………………............ 76
5.1.2.3 Wear Indicating Parameters …………………………. 78
5.1.2.4 Microstructure and Micro-hardness …………………. 80
5.1.3 Findings From Stage-I of Pilot Experiments ……………. 81
5.2 Results and Analysis of Stage-II of Pilot Experiments ……….. 82
5.2.1 Effects of Electrolyte Flow Rate and Rotary Speed on Surface Roughness ………………………………………… 83
5.2.2 Analysis of the Best Finished Gear ………………………... 84
5.2.2.1 Micro-geometry ………………………………………. 84
5.2.2.2 Gear Tooth Flank Topology ………………………….. 86
5.2.2.3 Microstructure and Micro-hardness …………………... 87
5.2.3 Findings from Stage-II of Pilot Experiments ……............. 89
5.3 Investigations on Role of Honing Gear Hardness ……………. 89
5.3.1 Hardening of Honing Gear by Plasma Nitriding …………. 90
5.3.2 Analysis of Surface Roughness …………………………... 91
5.3.3 Analysis of Micro-geometry ……………………………… 92
5.3.4 Analysis of Gear Tooth Flank Topology …………………. 93
5.3.5 Analysis of Microstructure ………………………………... 96
5.3.6 Analysis of Micro-hardness ………………………………. 97
5.3.7 Findings from the Investigations …………………........ 98
5.4 Results and Analysis of Main Experiments ………………….. 98
5.4.1 Analysis of Surface Roughness, Micro-geometry, MRR … 101
5.4.1.1 Effect of Applied Voltage …………………………… 101
5.4.1.2 Effect of Electrolyte Composition …………………... 104
5.4.1.3 Effect of Electrolyte Concentration …………………. 107
5.4.2 Analysis of the Best Finished Gear ………………………. 109
5.4.2.1 Surface Roughness, Material Ratio Curve and Waviness ………………………………………… 109

5.4.2.2 Micro-geometry ………………………………………... 111
5.4.2.3 Gear Tooth Flank Topology ………………………... 111
5.4.2.4 Wear Indicating Parameters …………………………. 114
5.4.2.5 Microstructure ………………………………………. 117
5.4.2.6 Micro-hardness and Residual Stresses ……………… 119
5.4.3 Findings from the Main Experiments …………………….. 119
5.5 Results and Findings of the Confirmation Experiment ……….. 120
Chapter 6: Theoretical Modeling and Validation ………………. 125-140
6.1 Development of Model for Volumetric MRR ……………… 126
6.2 Development of Model for Surface Roughness Depth ……... 131
6.3 Validation of the Developed Models ……………………….. 135
6.4 Findings from Theoretical Modeling ………………………. 140
Chapter 7: Comparison of Process Performance ………………. 141-153
7.1 Comparison of PECH with PECF ………………………... 141
7.2 Comparison of PECH with ECH …………………………… 145
7.3 Specific Energy Consumption in PECH and ECH ……..….. 149
7.4 Findings from the Comparative Study ……………………… 152
Chapter 8: Conclusions and Scope for the Future Work ………. 155-158
8.1 Significant Achievements …………………………………….. 155
8.2 Conclusions ……………………………………………………... 156
8.3 Directions for the Future Research …………………………… 158
References ………………………………………………………... 159-163
Appendix-A: Details of the Measuring Instruments …………….. **165-169**
Appendix-B: Results of ANOVA **171-172**

List of Figures

Figure Number and its Caption	Page No.
Fig. 1.1: Photographical representations of (a) unfiltered primary profile (P-profile); (b) average surface roughness; and (c) maximum surface roughness and depth of surface roughness	4-5
Fig. 1.2: Concept of (a) measurement of profile error of a gear, computation procedure of (b) total profile error ($F_α$); (c) profile form error ($f_{fα}$); and (d) profile angle error ($f_{Hα}$).	6
Fig. 1.3: Concept of (a) measurement of lead error of a gear, computation procedure of (b) total lead error ($F_β$) and its two components namely (c) lead form error ($f_{fβ}$) (d) lead angle error ($f_{Hβ}$).	8
Fig. 1.4: Concept of (a) measurement of pitch error and runout; (b) single pitch error; (c) cumulative pitch error; and (d) runout.	9
Fig. 1.5: Goals of a finishing a gear and means of achieving them.	15
Fig. 1.6: Surface characteristics of a gear that can be improved by finishing process.	15
Fig. 1.7: Schematic of transverse gear shaving process.	17
Fig. 1.8: Illustration of gear burnishing process.	18
Fig. 1.9: Schematic of internal honing of an external gear.	19
Fig. 1.10: Schematic of gear lapping process.	20
Fig. 1.11: Schematic of gear grinding process.	21
Fig. 1.12: Design of cathode gear for finishing of cylindrical gears by ECH given by **Chen *et al.* (1981)**.	25
Fig. 1.13: Photographs of machining chamber for high quality finishing of (a) spur gear **Naik *et al.* (2008)**; and (b) helical gear **Misra *et al.* (2010)**, by the ECH process.	25
Fig. 1.14: Concept of twin-complementary cathode gear (**Shaikh *et al.* 2013**) for bevel gear finishing by ECH.	26
Fig. 3.1: Experimental apparatus developed for finishing of straight bevel gear by PECH (a) schematic diagram; and (b) its photograph.	38-39
Fig. 3.2: Photograph of the finishing chamber for PECH of straight bevel gears.	40
Fig. 3.3: Rubber sealed radial ball bearings of stainless steel used to mount and support shafts holding cathode and honing gears.	40

Fig. 3.4: Drawing of shaft used to mount the honing and cathode gears. 40

Fig. 3.5: Drawing of shaft used to mount the workpiece gear. 41

Fig. 3.6: Drawing of the connector used to connect the workpiece shaft to the spindle of the drilling machine. 41

Fig. 3.7: Photograph of programmable DC pulsed power supply unit. 42

Fig. 3.8: Components of DC pulsed power supply used for finishing the bevel gears by PECH. 42

Fig. 3.9: Photograph of the shaft mounted on stainless steel block holding cathode gears and slip ring and carbon brush assembly. 43

Fig. 3.10: Assembly of carbon brushes and slip rings for the workpiece gear. 43

Fig. 3.11: Photograph of the stainless steel centrifugal pump used to supply electrolyte in the finishing chamber. 44

Fig. 3.12: Photograph of the double-stages magnetic filters used in the flow path of electrolyte supplied to the finishing chamber. 45

Fig. 3.13: Photograph of the (a) stainless steel pressure gauge; and (b) rotameter. 45

Fig. 3.14: Photograph of the (a) heating element; (b) temperature controller; and (c) temperature sensor. 45

Fig. 3.15: Schematic of the designed system for providing the reciprocating motion to the workpiece. 46

Fig. 3.16: (a) Photograph of the blanks of copper and metalon prepared for fabrication of the complementary cathode gears **(b)** photographs of the complementary cathode gears. 47

Fig. 3.17: Drawing of (a) honing and cathode gears and photograph of honing gear; and (b) workpiece gear and its photograph. 48

Fig. 4.1: Geometric representation of central composite design of RSM for three parameters varying at five levels each and three replicates of the centre point. 57

Fig. 4.2: Geometric representation of Box-Behnken design of RSM for three input parameters varying at three levels each and three replicates of the centre point. 58

Fig. 4.3: Details of experimental investigations for different types of experiments. 60

Fig. 5.1: Variation of *avg.* PIR_a and *avg.* PIR_{max} with (a) pulse-on time (T_{on}); (b) pulse-off time (T_{off}); and (c) finishing time (t). 71 - 72

Fig. 5.2: Variation of average value of percentage improvement in depth of surface roughness (*PIR_z*) for the specimen finished in the different experimental runs. 72

Fig. 5.3: Variation of percentage improvements in average values of single pitch error *(PIf_p)*, adjacent pitch error *(PIf_u)* and cumulative pitch error *(PIF_p)* and for runout *(PIF_r)* with (a) pulse-on time; (b) pulse-off time; and (c) finishing time. 72 - 73

Fig. 5.4: Roughness profile of bevel gear along the evaluation length for (a) an unfinished gear; and (b) same gear finished using the identified optimum values of pulse-on time, pulse-off time and finishing time. 75

Fig. 5.5: Material ratio curve of the gear tooth flank surface (a) unfinished gear; and (b) same gear after finishing by PECH using the identified optimum values of pulse-on time, pulse-off time and finishing time. 76

Fig. 5.6: Single pitch error *'f_p'* and adjacent pitch error *'f_u'* of bevel gear (a) before finishing by PECH; and (b) after finishing by PECH using the identified optimum values of pulse-on time, pulse-off time and finishing time. 77

Fig. 5.7: Cumulative pitch error *'F_p'* and runout *'F_r'* of straight bevel gear (a) before finishing by PECH; and (b) after finishing by PECH using the identified optimum values of pulse-on time, pulse-off time and finishing time. 77

Fig. 5.8: Wear indicating parameters (a) coefficient of sliding friction; and (b) friction force, of an unfinished bevel gear and the gear finished by PECH using identified optimum values of pulse-on time, pulse-off time and finishing time. 78

Fig. 5.9: Microstructure of wear test on gear tooth at 500X magnification for (a) an unfinished gear; and (b) the best finished gear by PECH using identified optimum values of pulse-on time, pulse-off time and finishing time. 79

Fig. 5.10: Microstructure of gear tooth flank surface at 500X magnification for (a) an unfinished gear; and (b) the best finished gear by PECH using the identified optimum values of pulse-on time, pulse-off time and finishing time. 80

Fig. 5.11: Micro-hardness profile of the bevel gear tooth flank for unfinished gear and the best finished gear by PECH using the identified optimum values of pulse-on time, pulse-off time and finishing time. 81

Fig. 5.12: Effect of (a) electrolyte flow rate; (b) rotary speed of workpiece gear, on avg. *PIR_a*, *avg. PIR_{max}*, and *avg. PIR_z*. 83

Fig. 5.13: Single pitch error *'f_p'* and adjacent pitch error *'f_u'* for (a) an unfinished gear; and (b) the best finished gear by PECH using identified optimum values of electrolyte flow rate and rotary speed of workpiece gear. 85

Fig. 5.14: Cumulative pitch error *'F_p'* and runout *'F_r'* for (a) an unfinished gear; and (b) the best finished gear by PECH using identified optimum values of electrolyte flow rate and rotary speed of workpiece gear. 85

Fig. 5.15: Tooth flank topology of the bevel gear; (a) unfinished; (b) best finished by PECH using the identified optimum values of electrolyte flow rate and rotary speed of workpiece gear. 87

Fig. 5.16: Microstructure of gear tooth flank surface at 400X magnification for (a) an unfinished gear; and (b) the best finished gear by PECH using the identified optimum values of electrolyte flow rate and rotary speed of workpiece gear. 88

Fig. 5.17: Schematic diagram of (a) hardening of honing gear by plasma nitriding process; (b) gear tooth profile of plasma nitrided honing gear. 90

Fig. 5.18: Photographs of the honing gears (a) a corroded unhardened honing gear; and (b) the plasma nitrided honing gear, after their continuous use in PECH process. 91

Fig. 5.19: Sequence of finishing the bevel gear by PECH process; (a) before finishing by PECH; (b) after electrolytic dissolution and formation of metallic oxide passivation layer; (c1) after honing action using an unhardened honing gear; and (c2) after honing action using the plasma nitrided honing gear. 92

Fig. 5.20: Tooth flank topology of the bevel gear; (a) before finishing; (b) after finishing by PECH using an unhardened honing gear. 94

Fig. 5.21: Tooth flank topology of the bevel gear; (a) before finishing; (b) after finishing by PECH using the plasma nitrided honing gear. 95

Fig. 5.22: Optical micrographs of the gear flank tooth surface (a) before finishing for gear 1; (b) gear 1 finished by PECH using an unhardened honing gear; (c) before finishing for gear 2; and (d) gear 2 finished by PECH using the plasma nitrided honing gear. 96

Fig. 5.23: Comparison of micro-hardness profiles of an unfinished bevel gear with the gear finished using an unhardened honing gear and the gear finished using plasma nitrided honing gear by PECH process. 97

Fig. 5.24: Variation of (b) average values of volumetric MRR, percentage improvements in average surface roughness (*avg.* PIR_a), maximum surface roughness (*avg.* PIR_{max}) and depth of surface roughness (*avg.* PIR_z); and (b) average percentage improvements in single pitch error (*avg.* PIf_p), adjacent pitch error (*avg.* PIf_u), cumulative pitch error (*avg.* PIF_p) and percentage improvement in runout (PIF_r), with the *voltage*. 103

Fig. 5.25: (a) Generation of passivation layer over the gear tooth flank; and (b) removal of passivation layer by the honing action. 104

Fig. 5.26: Variation of (a) average values of volumetric MRR, percentage 106

improvements in average surface roughness (*avg.* PIR_a), maximum surface roughness (*avg.* PIR_{max}) and depth of surface roughness (*avg.* PIR_z); and (b) average percentage improvements in single pitch error (*avg.* PIf_p), adjacent pitch error (*avg.* PIf_u), cumulative pitch error (*avg.* PIF_p) and percentage improvement in runout (PIF_r), with the *electrolyte composition.*

Fig. 5.27: Microstructure of flank surface of a bevel gear tooth showing passivation layer which could not be removed by honing gear in PECH process while using electrolyte composition of 25 wt.% NaCl + 75 wt.% $NaNO_3$. 107

Fig. 5.28: Variation of (a) average values of volumetric MRR, percentage improvements in average surface roughness (*avg.* PIR_a), maximum surface roughness (*avg.* PIR_{max}) and depth of surface roughness (*avg.* PIR_z); and (b) average percentage improvements in single pitch error (*avg.* PIf_p), adjacent pitch error (*avg.* PIf_u), cumulative pitch error (*avg.* PIF_p) and percentage improvement in runout (PIF_r), with the *electrolyte concentration*. 108

Fig. 5.29: Surface roughness profiles and material ratio curves for a bevel gear tooth flank for (a) an unfinished gear; and (b) the same gear finished by PECH using the identified optimum values of applied voltage, electrolyte composition and electrolyte concentration. 110

Fig. 5.30: Variation in waviness profile of a bevel gear tooth flank for (a) an unfinished gear; and (b) the same gear finished by PECH using the identified optimum values of applied voltage, electrolyte composition and electrolyte concentration. 110

Fig. 5.31: Gear metrology report showing improvement in single pitch deviation 'f_p' and adjacent pitch deviation 'f_u' for (a) an unfinished gear; and (b) the same gear finished by PECH using the identified optimum values of applied voltage, electrolyte composition and its concentration. 112

Fig. 5.32: Gear metrology report showing improvement in cumulative pitch deviation 'F_p' and runout 'F_r' for (a) an unfinished gear; and (b) the best finished gear by PECH using the identified optimum values of applied voltage, electrolyte composition and its concentration. 112

Fig. 5.33: Gear tooth flank topology of a bevel gear tooth for (a) an unfinished gear; and (b) the best finished gear by PECH using the identified optimum values of applied voltage, electrolyte composition and its concentration. 113

Fig. 5.34: Variation in (a) coefficient of sliding friction; and (b) sliding friction force, with the testing time for an unfinished gear and the best finished gear by PECH using the identified optimum values of applied voltage, electrolyte composition and electrolyte concentration. 115

Fig. 5.35: SEM micrographs of the wear track and surrounded area of a gear tooth flank surface at 500X (a) an unfinished gear; and (b) the best finished gear by PECH using the identified optimum values of applied voltage, electrolyte composition and electrolyte concentration. 116

Fig. 5.36: SEM images (at 500X magnification) depicting microstructure of the gear tooth flank surface of (a) an unfinished gear; and (b) gear tooth flank having passivation layer; and (c) best finished gear by PECH using the identified optimum values of applied voltage, electrolyte composition and its concentration. 117 - 118

Fig. 5.37: Microstructure of gear tooth flank surface at 300X magnification (a) unfinished gear; and (b) gear finished by PECH using the identified optimum input parameters during pilot and main experiments. 122

Fig. 6.1: Geometric parameters of a gear tooth. 129

Fig. 6.2 (a) Construction of the involute profile; and (b) construction of the length of chord. 129

Fig. 6.3: Microscopic view of sequence of smoothening of surface irregularities on flank surface of a bevel gear tooth by PECH process. 132

Fig. 6.4: Comparison between the values predicted by the proposed theoretical models and experimental values for (a) volumetric MRR; and (b) depth of surface roughness 'R_z' for straight bevel gears finished by PECH for the different validation experiments. 137

Fig. 6.5: Effect of applied voltage, pulse-on time and pulse-off time on the values predicted by the proposed theoretical models and experimental values of (a) volumetric *MRR;* and (b) depth of surface roughness 'R_z' for k = 0.1. 139

Fig. 7.1: Surface topography of (a) an unfinished gear; and (b) same gear finished by PECF using optimum process parameters identified from pilot and main experiments. 143

Fig. 7.2: Surface topography of (a) an unfinished gear; and (b) same gear finished by PECH using optimum process parameters identified from pilot and main experiments. 144

Fig. 7.3: Microstructure of bevel gear tooth flank surface at 300X magnification of (a) an unfinished gear; (b) a gear finished by PECF; and (c) a gear finished by PECH, using the optimum process parameters identified from pilot and main experiments. 144

Fig. 7.4: Photograph of finishing chamber showing design of cathode gear and its arrangement with respect to the workpiece and honing gears for bevel gear finishing developed (a) by **Misra *et al.* (2013)** for ECH; (b) by **Shaikh *et al.* (2013)** for ECH; and (c) in present work by PECH. 145 - 146

Fig. 7.5: Microstructure of gear tooth flank surface reported by **Shaikh *et al.*** 150

(2013) for their (a) unfinished gear; and (b) the ECH-finished gear by them, reported by **Misra *et al.* (2013)** for their (c) unfinished gear; and (d) the ECH-finished gear by them, reported in the present work (at 500X magnification) for (e) an unfinished gear; and (f) PECH-finished gear.

Fig. 7.6: Surface roughness profile of bevel gear tooth flank reported by Shaikh *et al.* (2013) for (a) an unfinished gear; and (b) the ECH-finished gear, reported in the present work for (c) an unfinished gear; and (d) the PECH-finished gear. 151

List of Tables

Table Number and its Caption	Page No.
Table 1.1: Different modes of gear failures (Davis, 2005).	2
Table 1.2: Effect of surface characteristics on various performance characteristics of a gear.	3
Table 1.3: Different manufacturing processes for cylindrical and conical gears.	13
Table 1.4: Applications of gears with respect to geometric accuracy.	14
Table 1.5: Summary of conventional finishing processes of the gears.	16
Table 1.6: Different process parameters of ECH and PECH and their typical values.	27
Table 3.1: Design parameters of cathode, honing and workpiece gears along with their material composition, properties and selection criteria.	49
Table 5.1: Results of the pilot experiments (stage-I) for surface roughness parameters.	67
Table 5.2: Results of the pilot experiments (stage-I) for micro-geometry parameters.	68
Table 5.3: Results of the pilot experiment (stage-II) for surface roughness parameters.	82
Table 5.4: Results of the pilot experiment (stage-II) for gear tooth flank topology.	86
Table 5.5: Comparison of surface roughness parameters of bevel gears finished using unhardened and plasma nitrided honing gear.	91
Table 5.6: Micro-geometry parameters of the bevel gears finished by PECH using unhardened and plasma nitrided honing gear.	92
Table 5.7: Results of gear tooth flank topology evaluation before and after finishing the bevel gears using the unhardened and plasma nitrided honing gear.	93
Table 5.8: Results of main experiments for the surface roughness parameters.	99
Table 5.9: Results of main experiments for the micro-geometry parameters.	100
Table 5.10: Results of tooth flank topology evaluation for an unfinished and the best finished gear by PECH.	114
Table 5.11: Results of confirmation experiment for all the considered	121

responses.

Table 6.1: Values of the different constants used in prediction of volumetric MRR and depth of surface roughness by their theoretical models for the validation experiments. 136

Table 6.2: Values of volumetric MRR and depth of surface roughness predicted by their theoretical models, corresponding experimental values and percentage error for different validation experiments. 136

Table 7.1: Results for process performance comparison of PECH with PECF in finishing of straight bevel gears. 143

Table 7.2: Comparison of process performance of PECH with ECH for bevel gear finishing. 147

Table 7.3: Comparison of specific energy consumption in ECH and PECH processes. 152

Table B.1: Results of ANOVA for average percentage improvements in average surface roughness (PIR_a), in maximum surface roughness (PIR_{max}) *for pilot experiments (stage-I)*. 171

Table B.2: Results of ANOVA for average percentage improvements in single pitch error, adjacent pitch error, cumulative pitch error and runout for pilot experiments (stage-I). 172

Nomenclature

A_f	Area of the tooth flank of the gear (mm^2)
A_s	Surface area of the bevel gear tooth surface where the electrolytic dissolution takes place through flow of current (mm^2)
A_T	Area of the top land (mm^2)
D_w	Total working depth of a gear tooth (mm)
E_w	Electrochemical equivalent of the workpiece material (gm)
f	Factor used to convert the height of a rectangle into height of a triangle with the same area and the base length
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
F_n	Total normal load acting along the line of action (N)
F_w	Face width of the bevel gear tooth (mm)
H	Brinell hardness number (BHN) of the workpiece gear material (N/mm^2)
h_{PECF}	Total thickness of the material removed from the flank surface of workpiece gear in one cycle of PECF (µm)
h_h	Total thickness of the material removed from the flank surface of workpiece gear in one cycle of mechanical honing (µm)
h_p	Distance between centre line of the cathode surface roughness and *peaks* on the flank surface of workpiece gear *before* PECF (µm)
h_v	Distance between centre line of the cathode surface roughness and *valley* on the flank surface of workpiece gear *before* PECF (µm)
h'_p	Distance between centre line of the cathode surface roughness and *peaks* on the flank surface of workpiece gear *after* PECF (µm)
h'_v	Distance between centre line of the cathode surface roughness and *valley* on the flank surface of workpiece gear *after* PECF (µm)
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 ($\Omega^{-1}mm^{-1}$)
L_c	Length of chord of the involute profile (mm)
L_{iw}	Length of the involute profile (mm)

N_s	Number of revolution of the workpiece gear per second (rps)
Q_{ECF}	Amount of material removed by electrochemical finishing (ECF) process
Q_{PECF}	Amount of material removed by PECF process during pulse-on time '$\boldsymbol{T_{on}}$'.
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)
$R_{Z_{PECF1}}$	Depth of surface roughness after one cycle of PECF (µm)
S	Total sliding distance (mm)
t	Finishing time (sec)
t_p	Total time of a single pulse (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)
W	Width at the base of the tooth (mm)
W_T	Width of top land (mm)
W_b	Width of bottom land (mm)
W_a	Average Waviness (µm)
W_{max}	Maximum Waviness (µm)
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
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
CNC	Computer Numeral Control
COF	Coefficient of Sliding Friction
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
FF	Friction Force
HMP	Hybrid Machining Processes
HRC	Rockwell Hardness on C-Scale
HV	Vicker's Hardness Number
IEG	Inter Electrode Gap
MRC	Material Ratio Curve
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
SEM	Scanning Electron Microscope
SS	Sum of Square
SSFC-ECH	Slow Scanning Filed Control Electrochemical Honing
SST	Total Sum of Square