Investigations on Near-Net Shape Manufacturing of Elliptical Helical Gears by Wire Spark Erosion Machining Process

M.Tech. Thesis

By

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Indian Institute of Technology Indore

July 2020

Investigations on Near-Net Shape Manufacturing of Elliptical Helical Gears by Wire Spark Erosion Machining Process

A Thesis

Submitted in partial fulfillment of the requirements

for the award of the degree

of

Master of Technology

in

Mechanical Engineering

with specialization in

Production and Industrial Engineering

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Declaration by Candidate

I hereby certify that the work which is being presented in the thesis entitled "**Investigations on Near-Net Shape Manufacturing of Elliptical Helical Gears by Wire Spark Erosion Machining Process"** in the partial fulfillment of the requirements for the award of the degree of **Master of Technology** in **Mechanical Engineering** with specialization in **Production and Industrial Engineering** and submitted in the **Department of Mechanical Engineering, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from **December 2018 to June 2020** under the supervision of **Prof. Neelesh Kumar Jain** of Department 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.

(Sandeep Gour)

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

(Prof. Neelesh KumarJain)

Sandeep Gourhas successfully completed his M.Tech. Viva held on **30th July 2020**

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30th July 2020

Signature of Chairman (with date), Oral Examination Board

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Sandeep Gour

Dedicated

to

My Family

Abstract

Non-circular gears (NCG) gears have teeth placed on circumference of a non-circular shape. NCG have different characteristics than the circular gears. In addition to power transmission, they can reduce unwanted torque, enhance the required torque, produce non-uniform rotation, generate the special motion required in control and automation mechanisms, convert constant input speed to variable speed, and generate start-stop-dwell type motion. Different types of NCG are used for different applications such as flow meters, chain transmission systems, transmissions of bike plates, oil pumps, chain belts of combustion engines, agriculture machineries such as trans-planters and fertilizer distributors, step-less shift components for instruments or vehicles, slow speed and heavy load fields, replacement of cam and linkages, and for generation of nonlinear relation between the pinion and the driven gear. Application areas of NCG are still being explored because existing ways of their manufacturing are limited, very difficult, inaccurate, time consuming, require high technical expertise, and are not suitable for their mass production. Many more practical application areas can be generated by developing or exploring an effective manufacturing process of NCG manufacturing.

Helical teeth on a gear provide silent, efficient and accurate operation to gears. Provision of helix angle to the teeth of gears enables them to engage gradually making their performance quieter and smoother as compared to straight teeth gears and therefore, they can be used for higher speed power transmission. To provide these properties in NCG, their teeth have to be made inclined. NCG due to their complicated shapes already difficult to manufacture and provision of teeth angle, makes their manufacturing more complex. Consequently, this research explores WSEM process for manufacturing of NCG having straight and inclined teeth on an elliptical blank, non-circular bevel gears and non-circular bevel-helical gears. Elliptical helical gears (EHG) are NGC which have inclined teeth on an elliptical gear blank. They have comparatively more practical applications particularly in the mechanisms which require irregular rotational motion i.e. pumps, bicycle chain drives, steering mechanism, and packaging and conveyor applications. Therefore, prime focus the present research is detailed investigations on manufacturing of EHG from 7.5 mm thick stainless steel 304 plate by WSEM process.

Experimental investigation was designed and conducted in four stages. Twenty exploratory experiments were conducted during the 1st stage of experimentation to assess feasibility of WSEM process to manufacture macro-sized and meso-sized non-circular

gears of different types namely elliptical spur gear (ESG), elliptical helical gear (EHG), and elliptical bevel gear (EBG). Eighteen experiments were conducted in stage-2 using Taguchi method of design of experiments to study effects of non-electrical parameters (parameters related to wire, dielectric and cutting speed such as wire tension, wire feed rate, dielectric pressure, and cutting speed overwrite) of WSEM process on the considered responses i.e. maximum and average surface roughness (R_{max} *and* R_a) of gear teeth flank surfaces, gear cutting time (T_c) and material loss (L_m) so as to identify their optimum values. Thirty experiments were conducted in Stage-3 using central composite design of response surface methodology to study influence of electrical parameters (i.e. pulse-on time, pulse-off time, servo voltage, peak current) of WSEM process on the considered responses parameters and to identify their optimum values. Grey relational analysis (GRA) and analysis of variance (ANOVA) of the experimental results were used to optimize the considered parameters of WSEM process. Finally, confirmation experiments were conducted which confirmed the optimized results. AutoCAD and ELCAM software were used for modelling and part-programming of all the elliptical helical gears manufactured by WSEM during all the experiments. Topography of flank surface, recast layer formation, heat affected zone and meshing were studies for the best quality EHG (having minimum values of the considered responses) manufactured by WSEM process.

This research work proves that WSEM is a suitable process for near-net shape manufacturing of EHG. The process is non-toxic, user-friendly, flexible, and easy-to-operate process which can be easily adopted by industries for mass production of EHG.

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Nomenclature

S_c	Cutting speed overwrite
I_p	Peak current
R_a	Average surface roughness
R_{max}	Maximum surface roughness
V_s	Servo voltage
T_{off}	Pulse-off time
T_{on}	Pulse-on time
V_p	Pulse peak voltage
F_w	Wire feed rate
W_p	Dielectric pressure
T_w	Wire tension

Abbreviations

AMP	Advanced Manufacturing Processes
ANOVA	Analysis of Variance
CCD	Central Composite Design
CNC	Computer Numerical Control
DOE	Design of Experiments
DOF	Degree of Freedom
EHG	Elliptical Helical Gears
EHBG	Elliptical Helical Bevel Gear
ESG	Elliptical Spur Gears
FE-SEM	Field Emission Scanning Electron Microscope
GRA	Gray Relational Analysis
NCBG	Non-circular Bevel Gears
NCBHG	Non-circular Bevel Helical Gears
NCG	Non-circular Gears
NCHG	Non-circular Helical Gears
RSM	Response Surface Methodology
SS	Sum of Square
SST	Total Sum of Square
WEDM	Wire Electric Discharge Machining
WSEM	Wire Spark Erosion Machining

Chapter 1

Introduction

Gear is an important mechanical element used to transmit mechanical energy in the form of motion, torque and speed. It is a common machine part having teeth placed on its outer or inner periphery and functions by engagement of its teeth with its mating gear. Gears are mounted on the shafts and they rotate with the shaft without any slip between them thus constituting a positive drive. Engagement or meshing of gear teeth with its mating gear cause its rotation and transfers power/motion to another shaft. Gears can be classified in different ways based on different parameters. One of the most important parameters is shape of the gear blank on which teeth are cut and according to it, gears can be classified into two categories:

- Circular Gears
- Non-circular Gears

1.1 Introduction to Circular Gears

Generally, the word gear is understood as circular gear in which teeth are uniformly placed around its circumference on a circular shaped gear blank. They can be further classified in number of ways. Two main classifications are:

(A) According to the position of teeth:

- External Gears
- Internal Gears

(B) According to the type of teeth:

- Straight Teeth Gears
- Inclined Teeth Gears
- Curved Teeth Gears

Figure 1.1 depicts different types of circular gears. Circular gears are used in gearbox of automobile and machine tool, differential in automobiles, clock mechanism, gear motors, gear pumps, surgical instruments, automobile and industrial power transmission, automobile windscreen wiper mechanism, power window, power steering mechanism, etc.

1.2 Introduction to Non-circular Gears (NCG)

Any gear in which gear teeth are cut on blank having other than circular shape is called a non-circular gear (NCG). Non-circular gear geometry is designed based upon the requirement of a specific motion pattern. An NCG engages with the another NCG to generate or transfer the motion and/or power. They are very good replacements of cams and linkages, automatic feed mechanisms, quick return motion mechanism and other similar mechanisms due to their comparatively more compactness, less space requirements, dynamic balance and ability to provide exact kinematic solutions.

Spur Gear

Helical Gear

Bevel Gear

Worm Gear

Rack and Pinion

Inrernal Gear

Fig. 1.1: Different types of circular gears.

1.2.1 Classification of NCG

Figure 1.2 shows different types of NCG. All the major classifications associated with circular gears are applicable to NCG also. Further, they can be classified according to following additional criteria also.

(A) According to the pitch curve:

- **Closed curve NCG:** Teeth are mounted on the periphery of a closed curve non-circular blank. It gives smooth and shock free operation. Examples are: elliptical, triangular, square, pentagonal shaped gears.
- **Open curve NCG:** In the open curve NCG, teeth are not mounted on the entire periphery of a non-circular blank but on some part of it, thus pitch curve is not fully closed. It causes sudden change in velocity. Spiral gears are example of open curve

NCG.

(B) According to the position of gear teeth:

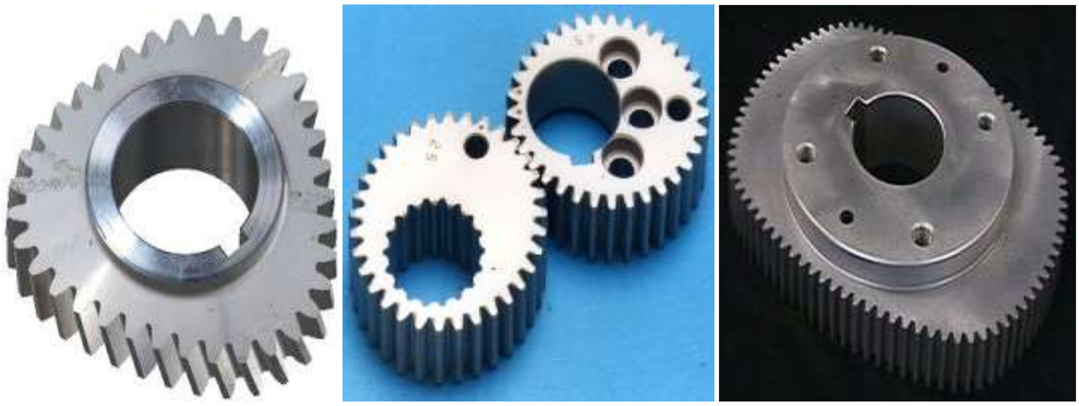
- External NCG
- Internal NCG

(C) According to the position of axes of revolution:

- Parallel shaft NCG (spur teeth NCG and helical teeth NCG)
- Intersection shaft NCG (bevel NCG)

(D) According to the number of lobes:

- N-lobed NCG (elliptical: 2 lobes, triangular: 3 lobes, square: 4 lobes, pentagonal: 5 lobes, etc.)



Triangular Gear   Elliptical/oval Gear   Square Gear

Spiral Gear   Non-circular Bevel Gear   Internal NCG

Fig. 1.2: Different types of non-circular gears (NCG).

1.3 Applications of NCG

NCG are used in following applications:

- To achieve variable power transmission,
- To convert constant input speed into variable speed and irregular motion like start-stop-dwell motion,

- To generate special purpose requirements such as start-stop-dwell motion,
- To reduce speed fluctuations in rotating shaft of automobiles and machineries,
- To reduce unwanted torque and enhance the required torque
- To produce non-uniform rotation,
- To generate specifically required motions like control and automation mechanisms,
- To get overall change in angular velocity,
- Replacement of bulky and long chain mechanisms like quick return mechanism, intermittent mechanism, cams and linkages, etc.
- In agricultural machineries such as trans-planters, fertilizer distributors, rice planting machine, etc.
- In textile machinery, potentiometers, CVTs (continuously variable transmissions), window shade panel drives, high torque hydraulic engines, winding machines, automatic feed machines, conveyers,etc.
- In press machines such as mechanical presses, printing presses, hydraulic press etc.
- In mechanical computing machines for generation of precise and non-linear functions.

1.4 Introduction to Elliptical Helical Gears (EHG)

A non-circular gear having teeth made on an elliptical shaped gear blank is known as elliptical gear. It is closed curve NCG. It can mesh with elliptical and other different shaped NCG of same module. When the inclined or angled teeth are cut on an elliptical gear then it is known as elliptical helical gear (EHG). Teeth inclination gives same advantages in an EHG as it gives in a circular helical gear. EHG provides higher amount of tooth contact during operation and imparts various properties in it. EHG provide gradual engaging, noise reduction and smoother operation as compared to straight teeth elliptical gears. Fig. 1.3 shows elliptical gear and EHG.

1.5 Advantages and Applications of EHG

Elliptical gears are used in those mechanisms which require irregular rotational motion such as oil pumps, bicycle chain drive, steering mechanism and in packaging and conveyor applications. They are also used in fluid handling devices, and in manufacturing of automatic machines used agriculture, printing and textile industries.

Elliptical Gear Elliptical Helical Gear

Fig. 1.3: Elliptical gear and EHG

EHG can change rotational speed of a shaft within the same rotation or turn due to their ability to change steady speed rotary motion into variable speed rotary motion within the same rotation. Some typical applications based on this concept are shown in Fig. 1.4. They can also be used for motion transfer, actuation, power transmission, automatic axes control, positioning, and automation in various machines, equipment and devices. In their all application areas, elliptical gears can be replaced by EHG to get more efficient, smoother and silent operation, and for heavy load applications. EHG are used between two parallel shafts to get desired output such as generation of specific motion, power transfer, speed control, etc.

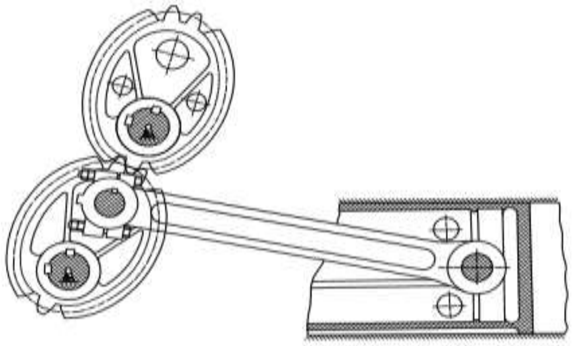


Fig. 1.4: Applications of EHG in fluid handling device and engine power transmission.

1.6 Materials for EHG

An EHG should be made from a material which suits its functional requirements. EHG material can be broadly classified into two categories:

- Metallic materials: Ferrous and non-ferrous materials
- Non-metallic materials: Plastics

Type of the EHG material depends on material characteristics, type of gear to be manufactured and type of the EHG manufacturing process. For heavy load applications, the EHG material should have high resistance to friction and wear, higher yield and fatigue strength to avoid failure and longer service life. Metallic materials are suitable for this purpose. For the corrosive environment applications, they should have higher corrosion resistant. EHG material should be light weight for smooth, silent and low-load applications. Plastics are suitable material for such requirements. Additionally, EHG material should be low cost to minimize the expenditure and increase economy in its manufacturing. Availability is also an important factor to fulfill its on-time availability and ease in inventory management.

1.7 Traditional Manufacturing of EHG

Manufacturing of NCG is very difficult due to requirement of manufacturing non-circular gear blank and then manufacturing teeth on this geometry. Other associated requirements such as manufacturing accuracy, repeatability, precision, good surface finish of the machined surfaces, ease of operation, low maintenance, operational and labor costs, and not causing any hazardous effects on the environment, make manufacturing of NCG extremely challenging. The selected manufacturing process should consume less energy and should fulfill the requirements of economic manufacturing of the NCG. All these requirements can be met by using an accurate manufacturing process for NCG.

Since EHG is key element of the actuating mechanisms, fluid handling and other motion generation and transmission devices; and widely used in automation therefore their tooth flank surface quality should be very good and profile should be accurately formed without any burr or any other machining residual. This will ensure satisfactory, efficient, smooth, and noiseless operation of EHG. Type of manufacturing process, machined surface roughness, and surface properties significantly affect quality, service life, and performance of the EHG. Therefore, their manufacturing should be highly precise and accurate.

Limited processes have been used for manufacturing of NCG. Hobbling, forging, shaping, copying and rolling are some traditional manufacturing processes used to manufacture NCG. But, quality of the manufactured NCG by these processes is poor thus requiring finishing processes. Moreover, tool marks, sharp edges, chips and burrs are some common problems associated with the traditional manufacturing processes. Moreover, these processes are not suitable for mass production due to low dimensional and geometrical accuracy of the manufactured NCG. Globally, manufacturing accuracy and loss of the material during the manufacturing are very important factors due to ever increasing costs of materials and manufacturing processes. Setting up of gear blanks on the machines used in the traditional processes is difficult thus requiring experienced machine operators. These processes need special tools and fixtures.

1.8 Quality Aspects of EHG

Poor quality of EHG adversely affects its operating performance characteristics (i.e. load carrying capacity, power and motion transmission characteristics, transmission efficiency, noise and vibrations related characteristics, non-uniformity in gear motion or wobbling, and reliability) and aspects of service life (i.e. fatigue strength, friction and wear characteristics, corrosion resistance). One of the important indicators of gear quality is tooth flank surface roughness because it significantly affects its fatigue strength, service life and operating performance. Maximum surface roughness *'R_{max}'* is more important than average surface roughness *'R_a'* value for the components such as gears, shafts, bearing, etc. which are subjected to fatigue and/or dynamic loading and severe working environment. Gear cutting time and material loss during manufacturing are important economic aspects during manufacturing of EHG. Smaller manufacturing time increases productivity of EHG manufacturing and smaller loss of the gear material reduces total cost of the manufactured EHG.

The present research work is considering industrial requirements also, so gear cutting time and material loss have taken under manufacturing quality consideration.

1.9 Introduction to WSEM Process

WSEM is a derived process of spark erosion machining (SEM) process. It is a thermal type advanced machining process. In this process material is removed by melting and vaporization of the work material by occurrence of series of discrete sparks in a very small inter-electrode gap (IEG) between a thin wire (cathode) and workpiece (anode) in the presence of a dielectric fluid. The dielectric fluid flushes away the eroded particles from the IEG and avoids formation of a recast layer on the machined surfaces. Generally, pressurized and continuously flowing deionized or distilled water is used as a dielectric fluid. It has lower dielectric strength and viscosity, higher cooling rate and absence of fire hazard. It implies use of very high pulse frequency. Use of an electrically conductive thin wire of few micron diameter as a generic tool significantly simplifies WSEM process as compared to SEM in terms of tool design. This eliminates need of any special tools and fixtures. The wire can be used to make complex geometry or cutting the desired 2D or 3D profile in an electrically conductive workpiece according to an offline prepared program on a computer numerical controlled (CNC) machine. Brass, copper, molybdenum, tungsten and zinc coated wires having diameter in the range from 100 to 300 µm can be used for WSEM. All these features help WSEM to overcome most of the limitations of the traditional manufacturing processes of gears.

WSEM machine consists of wire feed system, dielectric supply system and pulsed DC power supply system. Cutting is performed by pulsed servomotor controller and by CNC program. The wire continuously fed from the wire spool via workpiece and recollected in a chamber. The deionized or distilled water is supplied through the nozzle attached to the upper and lower guides to supply it concentrically with the wire. This flushes the eroded particles away from the IEG. WSEM machines have high efficiency, accuracy, repeatability and productivity. It has enabled this process to provide the best alternative to manufacture complex shapes, those required multi axes cutting.

Modern WSEM machines are CNC and equipped with features of machining the inclined surfaces which helps in machining different complicated shapes. CNC part programming of wire-path using the in-built software make WSEM capable of near-net manufacturing of circular and non-circular gears and providing inclined teeth to any non-circular shaped gear blank thus enabling near-net manufacturing of any type of NCG including EHG. Manufacturing of the components as per the requirement of shape, size with better surface finish significantly depends on proper selection of WSEM process parameters. Different parameters of WSEM can be categorized as follows:

- **Electrical parameters:** pulse peak voltage 'V_P', servo voltage 'V_s', peak current 'I_P', pulse-on time 'T_{on}', pulse-off time 'T_{off}'
- **Non-electrical parameters (or parameters related to wire and dielectric):** wire material, wire diameter 'd_w', wire feed rate 'F_w', wire tension 'T_w', dielectric flow rate 'P_w', dielectric pressure, cutting speed overwrite 'S_c'

1.9.1 Applications of WSEM Process

WSEM process has become a necessity in many industries and research organizations. Some typical fields of applications include:

- Tool and die making industries
- Automotive industries
- Aerospace and aircraft industries
- Healthcare industries
- Electronic industries
- Defense industries
- Other applications such as tool room jobs

Organization of the Thesis

This thesis has been divided into following five chapters:

Chapter 2: Presents review of the relevant past works on manufacturing of elliptical and other types of NCG using different manufacturing processes. It also presents identified research gaps, research objectives and research methodology of the present researchwork.

Chapter 3: Provides details of selection of type of NCG, selection of the material, EHG specifications, selection of the manufacturing process, planning, design and procedure of the experimental investigations for different stages. It also describes evaluation and characterization of the parameters related to surface roughness parameters, gear cutting time, and material loss during the manufacturing process.

Chapter 4: Describes results and discussions of different stages of experiments, their analyses and conclusions. It also presents results of optimization of WSEM process by GRA and ANOVA.

Chapter 5: Presents significant achievements, conclusions from the present research work and scope for the future research.

Chapter 2

Review of Past Work and Research Objectives

This chapter presents review of the past research work performed on manufacturing of NCG by different manufacturing processes. Reviewed literature is related to manufacturing of non-circular gears and elliptical gears with straight teeth and inclined teeth. It focuses on manufacturing of different types of NCG by different processes. It describes the identified research gaps, objectives of the present research work and the research methodology used in this research work.

2.1 Past Work on Manufacturing of NCG

Very limited work has been done on manufacturing of NCG. Most of the researchers have developed models for different types of NCG and simulated their manufacturing. Following paragraphs briefly describe the relevant past work.

Laczik*et al.* (2007) did modeling of NCG and calculated rolling curve and profile teeth for the given transfer function using maple R10 software. The process is not applicable to non-circular helical gear (NCHG) and non-circular bevel gear (NCBG).

Litvin*et al.* (2007) used enveloping process to generate surfaces of planar elliptical gears and computerized this process by applying existing equipment and tools. They proposed matrix approach and developed equation of meshing. They applied the developed theory for generation of planar and helical elliptical gear (EHG). They studied manufacturing of EHG using rack-cutter, hob, and shaper. Their study involves complex computations for designing of an NCG.

Shi *et al.* (2012) proposed design process for higher order NCBG having concave pitch curve and developed parametric equations in spherical coordinates for the driving and driven NCBG, addendum and dedendum surface for a given transmission ratio and axis angle. They developed 3D model for NCBG to verify the correctness of proposed design process which involves complex computations for designing of NCBG. They simulated process of enveloping NCBG by bevel gear cutter without physically manufacturing any NCBG.

Xia *et al.* (2013) developed linkage model for manufacturing of elliptical spur gear (ESG i.e. elliptical gear having straight teeth) using steel-45 as a gear material. High speed steel hobs were used to manufacture the gear. They used hobbing process to manufacture the gear. The process is long and involves difficult computations.

Zheng *et al.*(2016) described basic concept of generation of conjugate non-circular spiral bevel gear (NCSBG) teeth surfaces using crown-gear and presenting the tooth surface geometries by the position vectors and normals. Their model requires complicated computations and fixtures and more than one machine settings to manufacture the NCSBG. They developed kinematical model of free-form machines. They verified the developed method by manufacturing a real pair of NCSBG by face-milling. This is analogous to manufacturing of spiral bevel and hypoid gears using CNC hypoid gear generators thus improving productivity of manufacturing. They obtained satisfactory contact patterns between the manufactured NCSBG which agrees well with those modeled using the CAE software.

García-Hernández*et al.*(2016) presented mathematical model and manufactured elliptical and oval gears by WSEM using the MATLAB software. The process is not applicable to NCHG and NCBG.

Zhuang *et al.* (2017) proposed design method and 3D simulation of the model of NCBG. They used hot forging with involvement of pre-forging stage and depicted temperature distribution, strain distribution and material flow for the forging process. Their design computation is complicated, and surface of the gear manufactured was not of good quality.

2.2 Identified Research Gaps

Following research gaps were identified based upon review of the relevant past work:

- No work has been reported on manufacturing of EHG by WSEM process.
- No work has been reported on manufacturing of EBG and EBHG by WSEM process.
- No work has been reported on WSEM process parameters optimization for manufacturing of EHG.
- No work has been reported focusing on tooth flank surface roughness, gear cutting time and material loss during EHG manufacturing.
- No work has been reported for post-manufacturing analysis of EHG manufactured by WSEM process.

2.3 Objectives of the Present Research Work

Xia et al (2013) in their research article mentioned that WSEM process cannot manufacture non-circular helical gear. This served as motivation to undertake the present research work with the following research objectives:

- To explore WSEM process to manufacture macro-sized and meso-sized non-circular gears of different types namely elliptical spur gear (ESG), elliptical helical gear (EHG), and elliptical bevel gear (EBG).

- To study the effects of non-electrical parameters of WSEM process (parameters related to wire, dielectric and cutting speed) such as wire tension, wire feed rate, dielectric pressure, and cutting speed overwrite on the considered responses i.e. maximum and average surface roughness (R_{max} and R_a) of gear teeth flank surfaces, gear cutting time (T_c) and material loss (L_m) so as to identify their optimum values.
- To study effects of electrical parameters pulse-on time, pulse-off time, servo voltage, peak current on the considered responses parameters so as to identify their optimum values.
- Optimization of the considered parameters of WSEM process.
- Confirmation of the optimized results.
- To study the flank topography and testing of the best quality EHG manufactured using the identified optimum parameters of WSEM process.

2.4 Research Methodology

Figure 2.1 depicts the research methodology used to meet the identified research objectives of the present research work.

The ***next chapter*** describes selection of type of NCG for investigations, material and manufacturing process used for manufacturing of EHG. It includes the design specifications of the EHG. It also gives details about planning and design of the experiments, and concepts and methods used in analyzing results of each experimental stage.

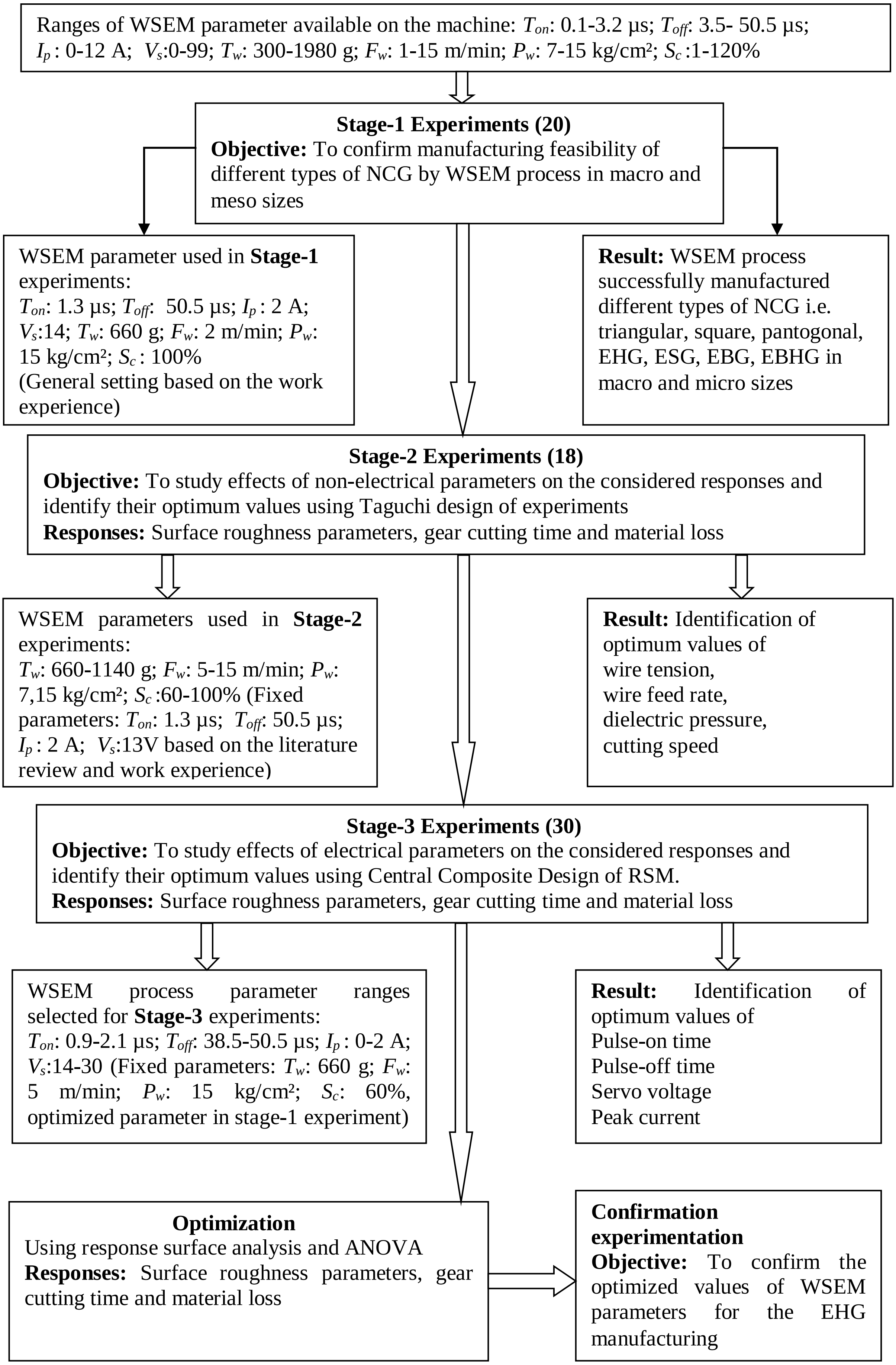


Fig. 2.1: Research methodology used in the present work.

Chapter 3

Details of Experimentation

This chapter describes details of selection of type, material, and specifications of NCG. It contains planning of experimental investigation in different stages, design of the experiments and selection of the WSEM parameters during each stage, evaluation of the responses, and concepts and methods used in the analyzing the experimental results.

3.1 Selection of the type of NCG

There are various types of NCG which can be manufactured according to the requirements. In the present research work the non-circular gear selected for the manufacturing and investigations is on the basis of its applications. Elliptical gears have comparatively more practical applications as compared to the other NCG. They are used in the mechanisms which required irregular rotational motion. Practical applications of elliptical gears include oil pumps, bicycles chain drives, steering mechanisms and in packaging and conveyor applications. Elliptical gears are used in different instruments, machines and systems and they can also be designed to serve special purposes according to the requirement of the present age and future machines. Inclined teeth have many advantages over straight teeth in the terms of noise reduction, operation smoothening and efficiency. On the basis of usage, flexibility of design and efficiency in operation, elliptical helical gear (EHG) i.e. elliptical shaped gear with inclined teeth, was selected for investigation in the present research work. More new practical application areas of EHG can be explored with the ease of their manufacturing on which the present research is focused.

3.2 Material Selection for the EHG

Material of EHG should be selected according to its intended use. The selected materials should enable the gear to perform satisfactorily and serve long service life without damage. EHG should be able to withstand in adverse conditions such as in heavy load applications, corrosive environments and highly stressed conditions. The material should be low cost from economy point of view and easily available to ensure ease in inventory management. Keeping these points in consideration, austenitic stainless steel of 304 grade was found suitable material and was selected as material for manufacturing EHG in the research work. SS304 is widely used in the various equipment and machines, food processing units, chemical plants, pharmaceutical, biomedical, surgical, and domestic applications due to its very good strength, higher resistance to corrosion and non-magnetic nature.

3.3 Specifications of the EHG

Table 3.1 presents details of the EHG manufactured and analyzed during used for experimental investigation of the present work. These values were decided mainly depending on its applications, size, material, manufacturing process and capabilities of the available measuring instruments.

Table 3.1: Specifications of the EHG manufactured in the present work.

Parameter	**Details**
Material	SS 304
Shape	Elliptical
Teeth type	Inclined (Helical)
Helix angle	20^{o} right hand type
Diametral pitch	20 mm
Module	1.27 mm
Pressure angle	20^{o}
No. of teeth	18
Face width	7.5 mm

3.4 Selection of Manufacturing Process

Manufacturing of NCG is a difficult task due to their complicated shapes. Multi-axes cutting is required for making a non-circular geometry and to cut teeth on it simultaneously. Provision of making helical teeth makes manufacturing of the EHG more complex. Following are some the desirable properties from manufacturing process of EHG:

- The process should not cause any adverse effect to the environment.
- The process should be economic.
- The process should be accurate and efficient in manufacturing.
- The process should be useful in mass production, once started it should be capable to manufacture number of gears, low associated maintenance with less manpower engagement.
- The process should be clean, user friendly, fast and flexible.
- The manufactured EHG should be free from unwanted matters and ready to use.

Since manufacturing of EHG requires generation of complex geometry, traditional manufacturing processes cannot be considered due to associated limitations such as difficult machine setting, poor machined surface quality, tool marks, chips, burrs, sharp edges and low geometrical and dimensional inaccuracy. Also, traditional processes are time consuming and require finishing processes after manufacturing of EHG. To overcome these limitations of the traditional processes, use of advanced manufacturing process (AMP) was considered. Focusing of the need of industries, continuous advancement and automation, wire spark erosion machining (WSEM) process was selected for the manufacturing of EHG. WSEM process is an AMP and can overcome the limitations of the traditional processes because of its following attributes:

- It does not cause any hazardous effect to the environment. The process is environment friendly.
- It is less costly because no complex machine setting is required. No highly skilled operator is required. Process once started, runs continuously and ends with completion of the program.
- It can manufacture complex geometries, intricate shapes and features.
- It has ability to manufacture near net-shape products.
- It is applicable to conductive materials irrespective of their hardness, brittleness and toughness.
- It can manufacture objects with good surface finish and dimensional accuracy.
- Ability to manufacture objects from very thin sheet to thickplate.
- It can produce smooth and crack-free surfaces without sharpedges, burrs, chips and other unwanted particles.
- Material loss is very small.
- It is fast and flexible.
- It can manufacture number of objects using same CNC program with less idle time.

3.5 Planning and Designs of Experiments

Proper planning and conducting of the experimental investigations always very helpful to achieve the goal. The experimental investigations were planned, designed and conducted in the following four stages using different design of experiments approaches to meet the identified set objectives of the present research work,

(a) **Stage1:** Exploratory Experiments

(b) **Stage-2:** Experiments for non-electrical parameters of WSEM

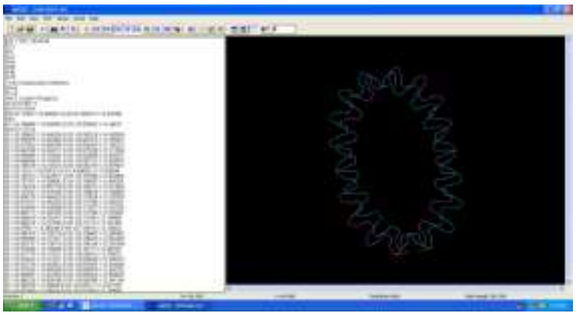
(c) **Stage-3:** Experiments for electrical parameters of WSEM

(d) Confirmation Experiments

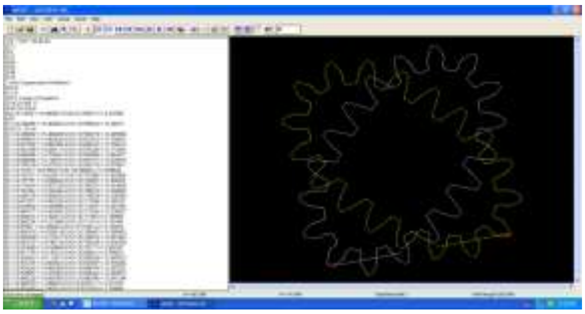
SprintCut-Win CNC WSEM machine from Electronica India Limited, Pune (India) was used with zinc coated brass wire of diameter 250μm (tolerance: + 0 to -2 μm, hardness: 550-750 N/mm^2) as wire and deionized water as a dielectric fluid were used in all the experiments.

3.5.1 Stage 1: Exploratory Experiments

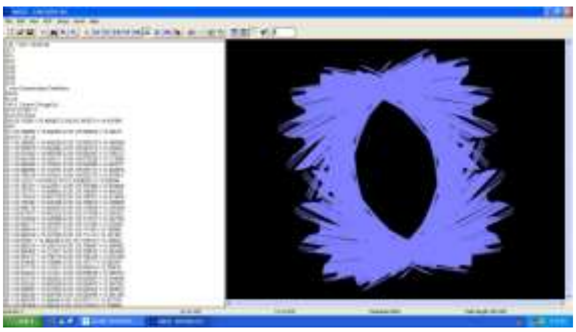
Twenty exploratory experiments were conducted during the 1st stage of experimentation to assess feasibility of WSEM process to manufacture macro-sized and meso-sized non-circular gears of different types namely elliptical spur gear (ESG), elliptical helical gear (EHG), elliptical bevel gear (EBG), elliptical bevel helical gear (EBHG), triangular gear, square gear, pentagonal gear. This required preparing CNC part programs for different types NCG. AutoCAD software was used to make model of the required NCG which is then transferred to the computer attached to the WSEM machine. ELCAM software was used to generate the wire path. Figure 3.1 shows different views of a part program. After successful generation and simulation of wire path in the ELCAM software, it was transferred to controller of the WSEM machine which confirms path travel by dry running of the prepared program. After making necessary corrections in the CNC programs and suitable parameter setting, actual manufacturing an NCG was done.



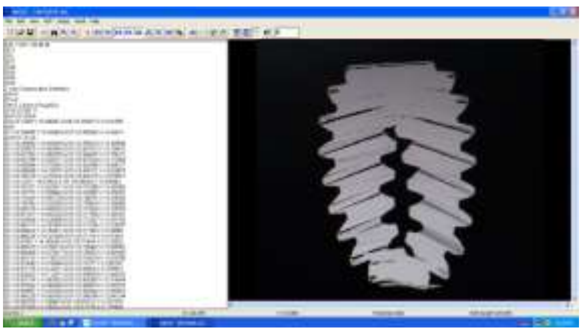
(a) Top layer and program height layer



(b) XY and UV axes travel



(c) Complete Wire Path



(d) 3D view of EHG

Fig. 3.1: Different views of wire path programmed by the ELCAM software.

WSEM process has number of process parameters which play important role during the machining process. Table 3.2 provides information about WSEM parameters, their available ranges in the machine units and actual units along with the increments availableon the WSEM machine used in the present work. Values of these parameters were selected using the criteria of wire deflection, frequency of wire breakage and cutting time of NCG. Table 3.3 presents the WSEM parameters used in 1st stage experiments. Entire gear geometry with all teeth was manufactured to check manufacturing capability of the WSEM process for different types of NCG.

Table 3.2: WSEM parameters and their available ranges/values on the *SprintCut-Win* WSEM machine and used in the **Stage-1** experiments.

Parameters (Units)	Symbol	Range (M/c units)	Increment (M/c units)	Range (Actual units)	Available increment	Used in Stage-1 experiments
Peak current (A)	I_p	0-30	1	0-30	1	2
Pulse peak voltage (V)	V_p	1-2	1	60-110	50	
Servo voltage (V)	V_s	0-99	1	0-99	1	13
Pulse-on time (μs)	T_{on}	100-131	1	0.1-3.1	0.1	1.3
Pulse-off time (μs)	T_{off}	0-63	1	3.5-50.5	0.5 (3.5-19.5) 1.0 (19.5-50.5)	50.5
Wire feed rate (m/min)	F_w	1-15	1	1-15	1	3
Wire tension (g)	T_w	1-15	1	300-1980	120	660
Dielectric pressure (kg/cm^2)	P_w	1-2	1	7-15	8	15
Cutting speed overwrite (%)	S_c	1-120	1	1-120	1	100

3.5.2 Stage-2: Experiments for Non-electrical Parameters

Stage-2 experiments were planned, designed and conducted with the objective to study influence of non-electrical parameters of WSEM process (i.e. wire tension, wire feed rate, dielectric pressure and cutting speed overwrite) on the considered responses i.e. maximum and average surface roughness (R_{max} and R_a) of gear teeth flank surfaces, gear cutting time (T_c) and material loss (L_m) and to identify their optimum values so that EHG of a good quality can be manufactured. Eighteen experiments were designed and conducted in Stage-2 using Taguchi L18 orthogonal array with mixed 2-3 level design of experiments approach. Wire tension (T_w), wire feed rate (F_w) and cutting speed overwrite (S_c) were varied at three levels each and dielectric pressure (W_p) was varied at its two levels. Whereas, four electrical parameters of WSEM process namely pulse-on time (T_{on}), pulse-off time (T_{off}), peak current (I_p) and servo-gap voltage (Vs) were kept constant at the values chosen based on literature review and past working experience on the machine. Table 3.3 presents values of the fixed and variable parameters used in the experiment. Grey relational analysis (GRA) was used to optimize the variable parameters using experimental data of Stage-2.

Table 3.3: Details of variable and fixed parameters and responses used in the **Stage-2** experiments.

<table>
<tr><th colspan="4">Variable parameters</th><th rowspan="3">Response parameters</th></tr>
<tr><td rowspan="2">Name and symbol (unit)</td><td colspan="3">Levels</td></tr>
<tr><td>I</td><td>II</td><td>III</td></tr>
<tr><td>Wire tension ‘T_w’ (g)</td><td>660</td><td>900</td><td>1140</td><td rowspan="9">• Maximum surface roughness
• Average surface roughness
• Gear cutting time
• Gear material loss</td></tr>
<tr><td>Wire feed rate ‘F_w’ (m/min)</td><td>5</td><td>10</td><td>15</td></tr>
<tr><td>Cutting speed overwrite ‘S_c’ (%)</td><td>60</td><td>80</td><td>100</td></tr>
<tr><td>Dielectric pressure ‘P_w’ (kg/cm²)</td><td>7</td><td>15</td><td>-</td></tr>
<tr><th colspan="3">Fixed parameters</th><td>Value</td></tr>
<tr><td colspan="3">Peak current ‘I_p’ (A)</td><td>2.5</td></tr>
<tr><td colspan="3">Pulse-on time ‘T_{on}’ (µs)</td><td>1.3</td></tr>
<tr><td colspan="3">Pulse-off time ‘T_{off}’ (µs)</td><td>50.5</td></tr>
<tr><td colspan="3">Servo-gap voltage ‘V_s’ (Volts)</td><td>13</td></tr>
</table>

3.5.3 Stage-3: Experiments for Electrical Parameters

Thirty experiments were conducted in Stage-3 using central composite design (CCD) of response surface methodology (RSM) to study influence of four electrical parameters of WSEM process (i.e. pulse-on time, pulse-off time, servo voltage and peak current) on the considered responses parameters by varying them at five level each and to identify their optimum values. The four non-electrical parameters were kept constant on their optimum values identified from the Stage-2 experiments. Table 3.4 presents values of the fixed and variable parameters used in Stage-3 experiments. Analysis of variance (ANOVA) of the experimental results was done to identify significant parameters and their interactions. Subsequently, quadratic regression models of the responses were developed in terms of the significant parameters and their interactions.

Table 3.4: Details of variable and fixed parameters and responses used in the **Stage-3** experiments.

<table>
<tr><th colspan="6">Variable parameters</th><th rowspan="3">Responses</th></tr>
<tr><td rowspan="2">Name and symbol (unit)</td><td colspan="5">Levels</td></tr>
<tr><td>I</td><td>II</td><td>III</td><td>IV</td><td>V</td></tr>
<tr><td>Pulse-on time ‘T_{on}’ (µs)</td><td>0.9</td><td>1.2</td><td>1.5</td><td>1.8</td><td>2.1</td><td rowspan="9">• Maximum surface roughness
• Average surface roughness
• Gear cutting time
• Gear material loss</td></tr>
<tr><td>Pulse-off time ‘T_{off}’ (µs)</td><td>38.5</td><td>41.5</td><td>44.5</td><td>47.5</td><td>50.5</td></tr>
<tr><td>Peak current ‘I_p’ (A)</td><td>0.5</td><td>0.5</td><td>1.5</td><td>2.5</td><td>2.5</td></tr>
<tr><td>Servo-gap voltage ‘V_s’ (Volts)</td><td>6</td><td>14</td><td>22</td><td>30</td><td>38</td></tr>
<tr><th colspan="5">Fixed parameters</th><td>Value</td></tr>
<tr><td colspan="5">Wire tension ‘T_w’ (g)</td><td>660</td></tr>
<tr><td colspan="5">Wire feed rate ‘F_w’ (m/min)</td><td>5</td></tr>
<tr><td colspan="5">Cutting speed overwrite ‘S_c’ (%)</td><td>60</td></tr>
<tr><td colspan="5">Dielectric pressure ‘P_w’ (kg/cm²)</td><td>15</td></tr>
</table>

3.5.4 Validation Experiments

Total 10 experiments were conducted to confirm the obtained results of the optimization. Identified optimum values of four non-electrical parameters from the Stage-2 experiments were used to conduct 5 confirmation experiments whereas identified optimum values of the four electrical parameters from the Stage-3 experiments were used to conduct five more confirmation experiments. In these experiments, standard values of the WSEM parameters (i.e. available on the WSEM machine) were used which were nearest to their optimized values and corresponding values of the responses were recorded. The values of responses obtained by confirmation experiments were compared with their corresponding initial values and with those obtained by the regression analysis.

3.6 Evaluation of the Responses

Details of the measurement process and equipment used for the measurement of surface roughness, gear cutting time and material loss during the manufacturing of EHG are described.

3.6.1 Evaluation of Flank Surface Roughness

Maximum and average values of flank surface (‘R_{max}’ and ‘R_a’) of the manufactured EHG during the experimental investigations were measured by 3D-surface roughness measuring-cum-contour tracing equipment ***LD130*** from ***Mahr Metrology, Germany*** (refer to appendix-A). The measurement was done on flank surfaces of the EHG by tracing 10 µm tip diameter probe at three different locations (i.e. middle and towards both the ends) using an evaluation length set of 1.0 mm; cut-off or sampling length as 0.08 mm; and Gaussian filter to distinguish between the roughness and waviness profiles. Arithmetic mean of 'R_{max}' and 'R_a' for each experimental run taken from their three values measured, were used for plotting the graphs and further analysis.

3.6.2 Measurements of the Gear Cutting Time

Time was recorded at the time of start of execution of the CNC program of an NCG and at the time of end of it by means of a calibrated digital clock with the least-count of one minute. Subtraction of program start time from the program end gave the time consumed in the manufacturing of the NCG by WSEM process.

3.6.3 Measurements of Gear Material Loss

Three measurements of the weight of the gear blank plate for NCG before the WSEM process and weight of the EHG manufactured were taken by a precision balance machine. Gear material loss was calculated by first adding the weights of gear blank plate after manufacturing NCG from it by WSEM and the weight of the NCG manufactured, and then subtracting it from total weight of the gear blank plate before manufacturing of the NCG.

3.7 Procedure of Experimentation

All the four stages of experiments were performed on the same WSEM machine following the same machine operating procedure. All the consumables and sequence of the different activities used in experimental investigations were same for each experiment.

3.7.1 Details of the WSEM Machine

CNC WSEM machine, *SprintCut-win* model from Electronica India Limited, Pune, (India) was used for manufacturing of EHG. It is shown in Fig. 3.2 and Table 3.5 provides its important specifications. It has fouraxes control namely X, Y,U, and V. It has press switch to control the Z axis. Control unit of the machine contains inbuilt machine computer, screen, keyboard and mouse to control the machine. Wire feed system contains set of rollers which operate when the machine starts functioning. Deionized water is supplied continuously by the dielectric supply unit. The water is recycled repeatedly because it becomes hot during the WSEM process. It has chiller unit is attached with it for cooling of the deionized water. Filtration unit filters the removed material particles and other impurities from the deionized water. It also has manual pulse generator (MPG) to control the machine manually. To control the discharge of water, control valves are provided.

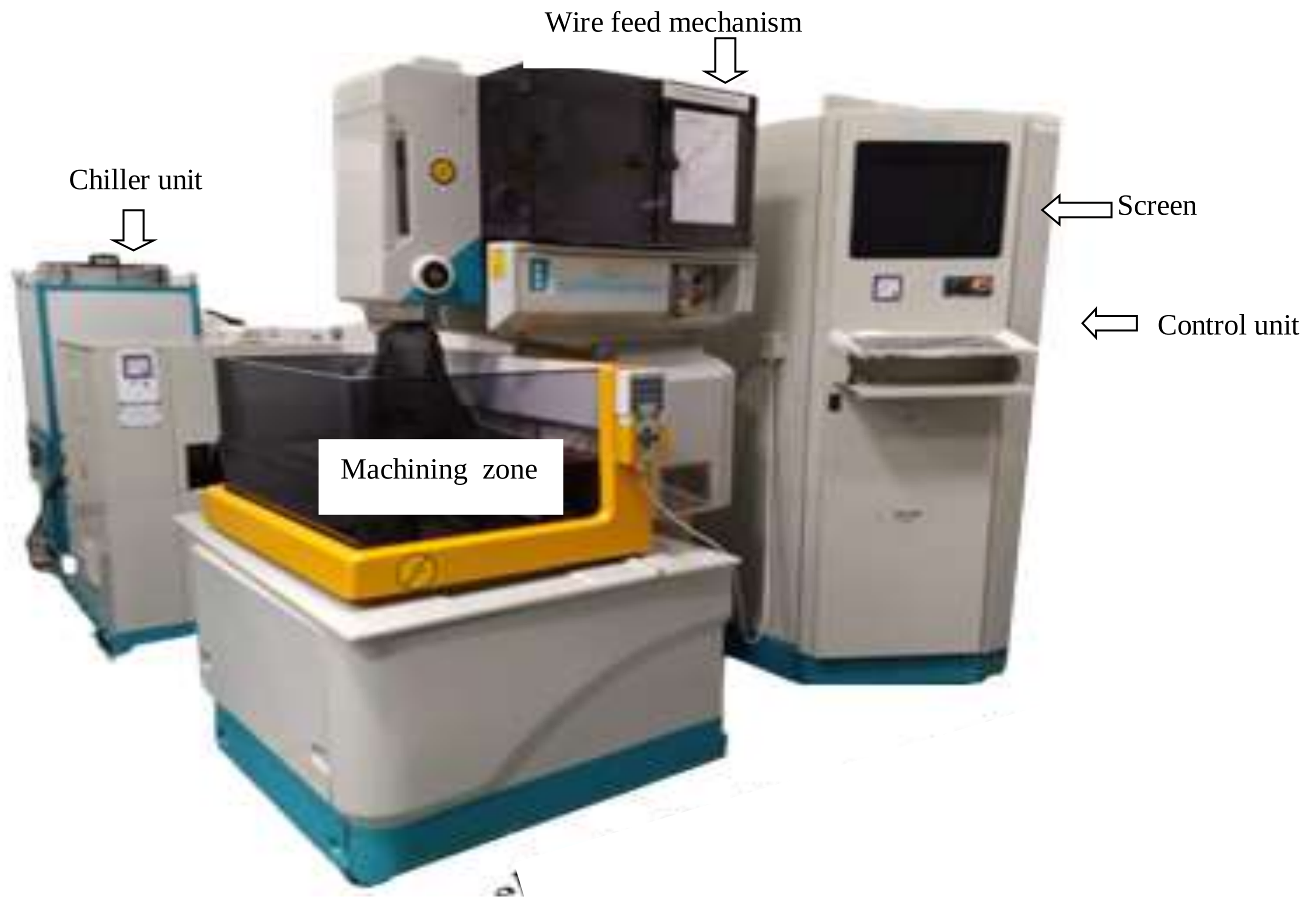


Fig. 3.2: Photograph of the *SprinCut-WIN*WSEM used in the present work.

Table 3.10: Specifications of CNC WSEM machine used in the present work.

Make	Electronica Machine Tools Ltd, Pune,India
Model	*SprintCut-Win*
Design	Fixed column, Moving table
Taper cutting	± 30^{o}/ 50mm
Table size	440 x 650 mm
Max. height and weight of workpiece	200 mm, 500 Kg
Traverse lengths of main table(x, y)	300, 400 mm
Traverse length of auxiliary table(u, v)	80, 80 mm
Diameter of wire electrode	150; 200; and 250µm
Dielectric type and tank capacity	De-ionized water; 350Ltrs.
Pulse power generator	ELPULS-40 ADLX
Input power supply	3 Phase, AC 415 V, 50HZ
Connected load	10 KVA
Average power consumption	6-7 KVA

3.7.2 Sequence of Activities in Manufacturing of NCG

Figure 3.3 shows different activities involved in manufacturing of an NCG by WSEM process during the experimental investigations, which is described below:

(i) Finishing of the rough plate of SS-304 by grinding and buffing processon its top and bottom faces. Ensuring the required plate thickness of 7.5 mm.

(ii) Drilling holes on the suitable places on the plate for easy wire entry so that the CNC program can be started from the middle of the plate.

(iii) Weight measurement of the workpiece plate before cutting of an NCG/EHG.

(iv) Loading of fresh zinc coated brass wire spool of 250 µm diameter wire and filling of deionized water up to the required level.

(v) Proper clamping of the prepared plate on the CNC WSEM machine worktable using clamps and bolts and ensure its perfect positioning with respect to the machine axes.

(vi) Loading the CNC program for manufacturing of NCG/EHG on the machine and confirming that the machine is fully ready for manufacturing of the NCG.

(vii) After setting the wire on the coordinate from where the CNC program is starting, confirming satisfactory working of the CNC program and checking axis limit by dry running of the CNC program.

(viii) Start actual running of the CNC program. Keeping record of the CNC program start time.

(ix) Removal of the workpiece plate and the gear manufactured after completion of the CNC program. Keeping record of the CNC program end time.

(x) Weight measurement of the gear manufactured and the remaining gear blank plate.

(xi) Measurement of the gear tooth flank surface roughness on surface roughness measurement machine.

The ***next chapter*** describes the results of different stages of the experiments and analyses, interpretations, and explanations of the obtained results.

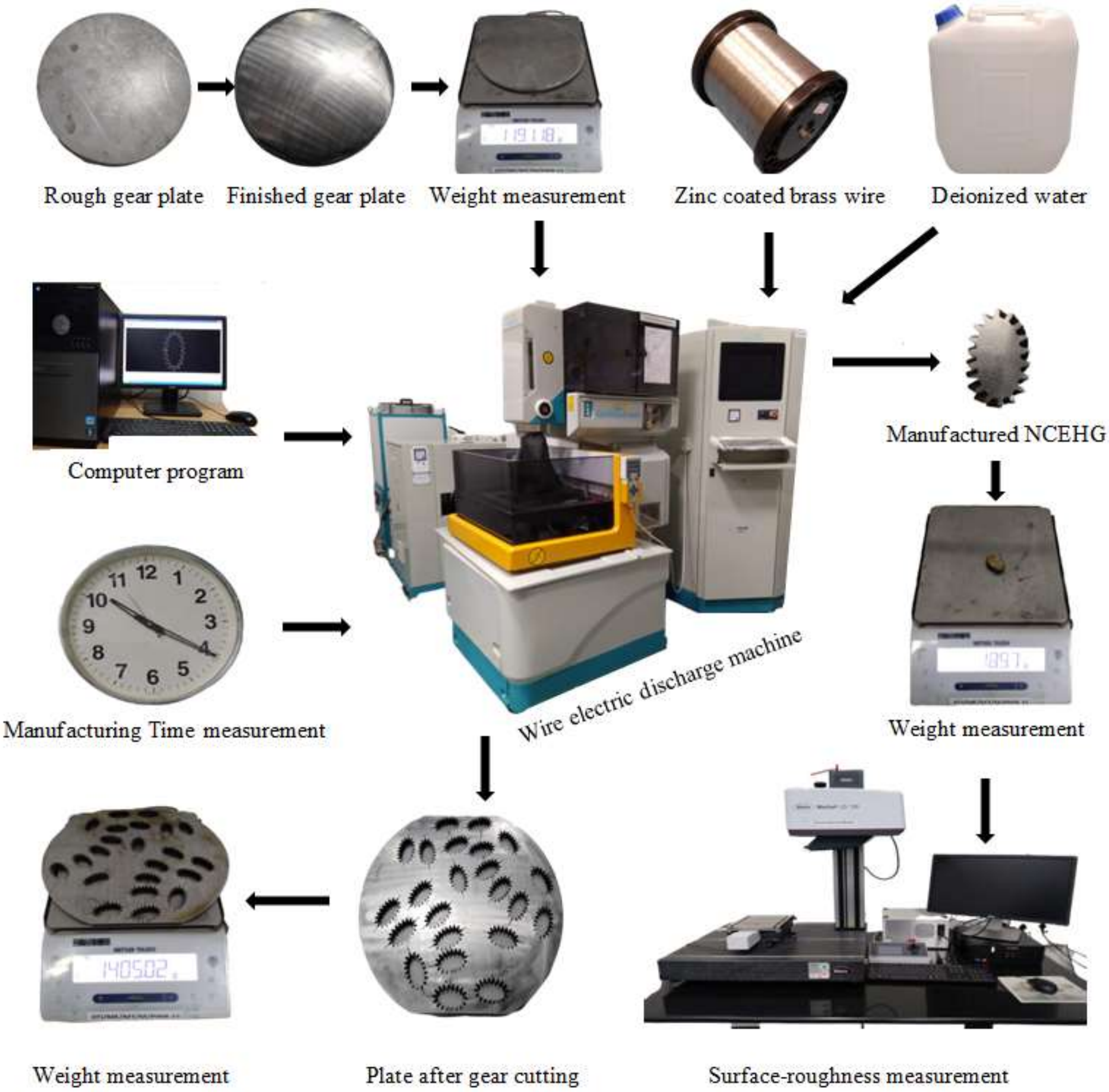


Fig. 3.3: Sequence of the different activities in manufacturing of EHG by WSEM process.

Chapter 4

Results and Analysis

This chapter describes the observations and results of the experiments planned and conducted in stage-1, stage-2, stage-3 and confirmation experiments. This includes analyses, explanations, interpretations and major conclusions drawn from eachstage of the experimentation.

4.1 Observations from the Stage-1 Experiments

Following are the observations of the 20 experiments conducted in the Stage-1 during which WSEM was explored for manufacturing macro and meso-sized different types of NCG using the WSEM parameters mentioned in the Table 3.2:

- Some corrections in the CNC programs are required according to the machine coordinate system used.
- The CNC program is complicated and too large therefore, it is difficult to download it from the PC to WSEM machine. It contains more than 6000 lines in a program.
- The CNC program can be split into parts to overcome the problems such as machine hanging, long program loading time, program loading failure etc.
- Wire breakage and machine stopping during the manufacturing of NCG must always be avoided due to any reason because restarting of the machine may cause wire marks, gap short problem, not restarting the program, machine hanging, etc.
- Machine should be calibrated before start of manufacturing of NCG/EHG to get manufacturing accuracy.

4.2 Results and Conclusions from the Stage-1 Experiments

WSEM manufactured different types of NCG in pairs which meshed successfully and were able to uninterrupted transfer power and motion. Figure 4.1 and 4.2 show different type of NCG manufactured in Stage-1 experiments and their meshing.

Oval gear | Elliptical gear | Triangular gear | Square gear | Pentagonal gear

Fig.4.1: Meso-sized NCG of different types manufactured in Stage-1 experiments (NB: notice board pin shows their relative size).

EHG EBG EBHG Meshing of oval gear

Meshing of elliptical gears Meshing of triangular gears

Meshing of square gears Meshing of pentagonal gears

Fig.4.2: Macro-sized NCG of different types manufactured in Stage-1 experiment and their meshing arrangements.

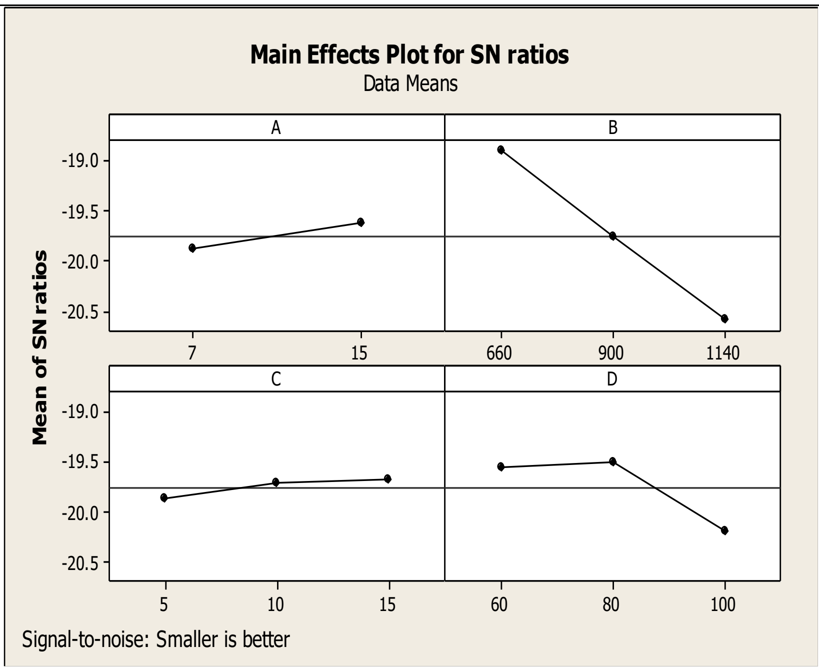
It can be concluded from the Stage-1 experiments that WSEM process can successfully manufacture different types of NCG in different sizes. The process has capability to manufacture straight and inclined teeth with good accuracy. It is also capable of manufacturing bevel NCG. It was observed that WSEM process is fast, user friendly and accurate process for NCG manufacturing and the process can be adopted commercially for the manufacturing of different types of NCG.

4.3 Results and Analysis of the Stage-2 Experiments

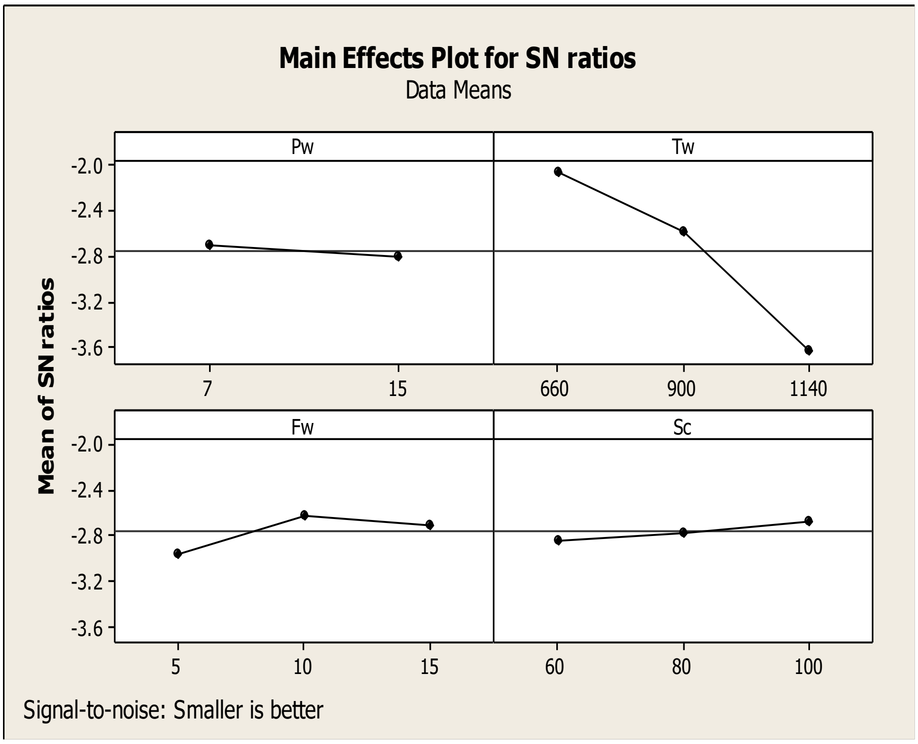
Table 4.1 presents results of Stage-2 experiments giving obtained values of the considered responses corresponding to parametric combinations of the 18 experimental runs. All considered responses (i.e. R_{max}, R_a, T_c and L_m) are *smaller-the-better* type therefore their minimum possible values are desirable. EHG teeth flank surfaces should have minimum values of roughness parameters for its efficient and friction-free operation. Time consumption in EHG manufacturing should be minimal for fast and large-scale production. Gear material loss should also be minimal because material saving leads to economy in production and controls the wastage of the resources. Considering these aspects, signal-to-noise ratio for the smaller-the-better type responses was selected for investigations. Higher value of signal-to-noise ratio represents optimum values of the parameters. Main effect plots for signal-to-noise ratio are shown in Fig. 4.3.

Table 4.1:Results of the **Stage-2** experiments for all the experimental runs.

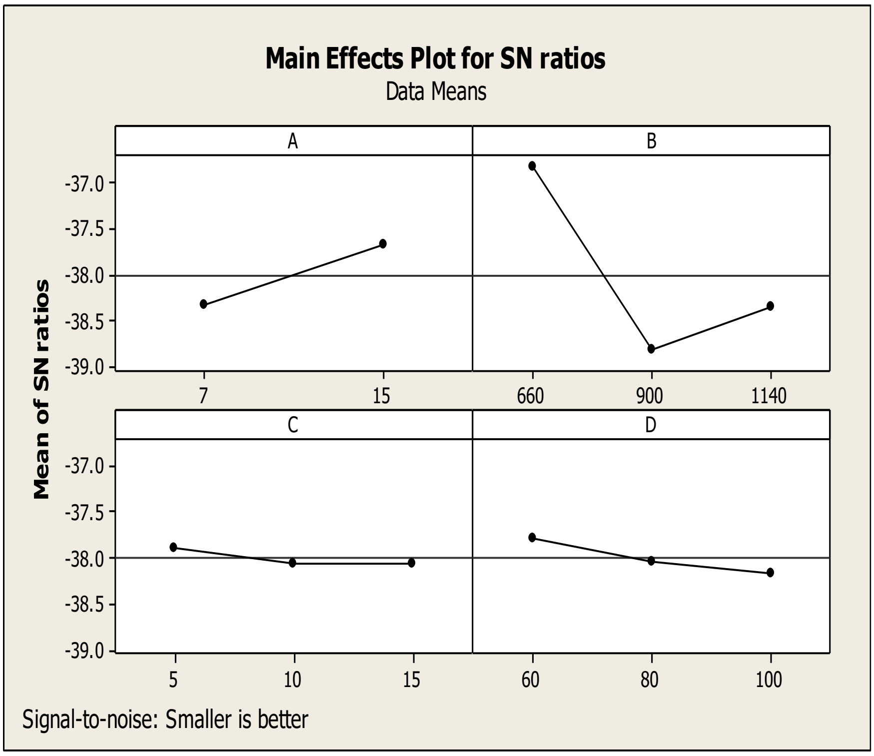
Exp. No.	W_p (kg/cm²)	T_w (g)	F_w (m/min)	S_c (%)	Responses R_a (μm)	R_{max}(μm)	T_c(min)	L_m(g)
1	7	660	5	60	1.13	8.15	65	3.43
2	7	660	10	80	1.30	9.80	67	3.56
3	7	660	15	100	1.40	8.34	69	3.54
4	7	900	5	60	1.63	10.53	94	2.59
5	7	900	10	80	1.28	8.78	99	3.52
6	7	900	15	100	1.23	12.09	101	4.87
7	7	1140	5	80	1.74	10.53	85	3.67
8	7	1140	10	100	1.35	12.76	88	3.65
9	7	1140	15	60	1.33	8.87	84	3.86
10	15	660	5	100	1.20	8.29	71	3.68
11	15	660	10	60	1.31	9.84	71	3.80
12	15	660	15	80	1.28	8.63	74	3.75
13	15	900	5	80	1.19	9.10	78	3.66
14	15	900	10	100	1.35	8.05	80	3.63
15	15	900	15	60	1.44	10.37	76	3.67
16	15	1140	5	100	1.68	13.34	81	3.60
17	15	1140	10	60	1.54	9.43	79	3.62
18	15	1140	15	80	1.53	10.02	80	3.61



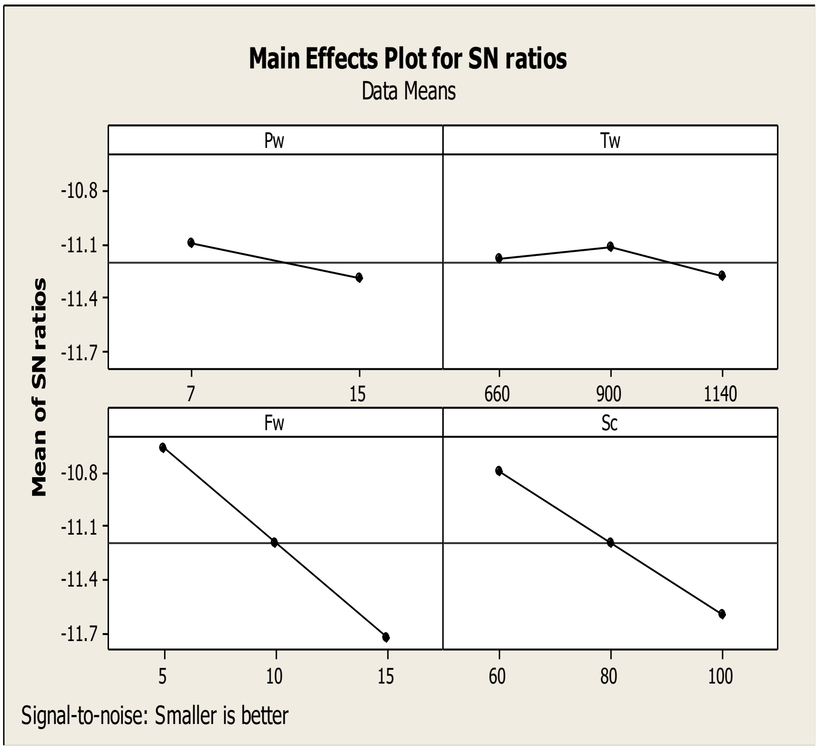
(a) Maximum value of flank surface roughness (R_{max})



(b)Average value of flank surface roughness (R_a)



(c) Gear cutting time (T_c)



(d) Gear material loss (*L_m*)

Fig. 4.3: Plots S/N ratiosof the considered responses with WSEM parameters.

Table 4.2 presents signal-to-noise ratios for the considered responses obtained from results of Stage-2 experiments. Table 4.3 mentions identified optimum values of four non-electrical parameters of WSEM process and the responses.

Table 4.2: Details of the S/N ratio for the considered responses.

(a) For R_{max}

Level	P_w	T_w	F_w	S_c
1	-19.88	**-18.90**	-19.86	-19.55
2	**-19.62**	-19.76	-19.71	**-19.51**
3		-20.59	**-19.68**	-20.20
Delta	0.27	1.69	0.18	0.69
Rank	3	1	4	2

(b) For R_a

Level	P_w	T_w	F_w	S_c
1	**-2.705**	**-2.056**	-2.953	-2.841
2	-2.812	-2.578	**-2.622**	-2.764
3		-3.641	-2.700	**-2.671**
Delta	0.107	1.585	0.331	0.170
Rank	4	1	2	3

(a) For T_c

Level	P_w	T_w	F_w	S_c
1	-38.33	**-36.83**	**-37.78**	**-37.80**
2	**-37.68**	-38.83	-38.06	-38.05
3		-38.36	-38.07	-38.17
Delta	0.65	2.00	0.18	0.37
Rank	2	1	4	3

(d) For L_m

Level	P_w	T_w	F_w	S_c
1	**-11.10**	-11.18	**-10.66**	**-10.79**
2	-11.29	**-11.12**	-11.20	-11.19
3		-11.29	-11.73	-11.60
Delta	0.19	0.17	1.07	0.81
Rank	3	4	1	2

Table 4.3: Identified optimum values of the non-electrical parameters of WSEM and the responses from the **Stage-2** experiments.

Response		**Non-electrical parameters of WSEM process**			
Name	***Value***	***P_w (kg/cm²)***	***T_w (g)***	***F_w (m/min)***	***S_c (%)***
R_{max} (μm)	7.8	15	660	15	80
R_a (μm)	1.12	7	660	10	100
T_c (min)	62	15	660	5	60
L_m (g)	2.57	7	900	5	60

It can be observed from Table 4.2 that:

- Maximum roughness of the EHG flank surfaces (R_{max}) is mainly influenced by T_w followed by S_c, P_w and F_w.
- Average roughness of the EHG flank surfaces (R_a) is mainly influenced by T_w followed by F_w, S_c and P_w.
- Gear cutting time (T_c) influenced mostly by T_w followed by P_w, S_c, and F_w.
- Gear material loss (L_m) is mainly influenced by F_w followed by S_c, P_w and T_w.

Table 4.3 shows results of the experiment.

4.3.1 Optimization Using Gray Relational Analysis

Taguchi analysis combined with grey relational analysis can be used to get optimum parametric combination of WSEM process for manufacturing of the EHG. It is very effective tools for multi-objective optimization having conflicting objectives such as in the present case i.e. surface roughness parameters, gear cutting time and gear material loss. Grey relational analysis converts the multi-objective optimization to a single-objective optimization problem and tries to identify the optimum parametric combination corresponding to the desired quality characteristics. Following steps were followed to perform grey relational analysis:

- **Normalization of the experimental data:** Using smaller-the-better criteria for normalization of all the responses (i.e. R_{max}, R_a, T_c, L_m) with the help of the following formula:

$$y_i^*(k) = \frac{max\, x_i^0(k) - x_i^0(k)}{max\, x_i^0(k) - min\, x_i^0(k)}$$

Where, i is index for experiment number, k is the index for the response or quality characteristics; $x_i^0(k)$is the experimental value of k^{th} response for i^{th} experiment, max

$x_i^0(k)$is maximum value of $x_i^0(k)$ and min $x_i^0(k)$is minimum value of $x_i^0(k)$.

- **Calculation of deviation sequence:** Using the following formula:

$$\Delta_{oi}\ (k) = \|y_0^*\ (k) - y_i^*\ (k)\|$$

$$\text{Where}, y_0^*(k) = 1, \text{maximum normalized value}$$

- **Calculation of gray relational coefficient (GRC):**Using the following formula:

$$\xi i(k) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{oi}(k) + \zeta\Delta_{max}}$$

Where, Δ_{min}= min $\|y_0^*\ (k) - y_i^*\ (k)\|$, Δ_{max}= max $\|y_0^*\ (k) - y_i^*\ (k)\|$, ζ = distinguish coefficient, Δ_{oi} (k) = offset in the absolute values of between the reference sequence$y_0^*(k)$ and the comparability sequence $y_i^*(k)$.

Table 4.4 presents details of the signal-to-noise ratios obtained for all the considered responses obtained by GRA and Fig. 4.4 shows their variation with input parameters. Table 4.5 presents values of grey relational coefficients (GRC) and grey relational grades (GRG) for the considered responses for all the runs of Stage-2 experiments.

Table 4.4: Details of S/N ratio obtained by grey relational analysis (GRA).

Level	P_w	T_w	F_w	S_c
1	-4.662	-2.992	-4.336	-4.254
2	-4.554	-4.812	-4.612	-4.612
3		-6.021	-4.876	-4.958
Delta	0.107	3.029	0.540	0.704
Rank	4	1	3	2

4.3.2 Confirmation of Optimization Results

Experiment was conducted using the GRA optimized WSEM parameters to confirm results of GRA. Table 4.6 presents the result of the confirmation experiment. Figure 4.4 presents different view of EHG manufacturing using the GRA optimized WSEM parameters.

Table 4.6: Results of the experiment conducted to confirm results by GRA.

Response	**Value**	***P_w* (kg/cm²)**	***T_w* (g)**	***F_w* (m/min)**	***S_c* (%)**
R_a (µm)	1.3	15	660	5	60
R_{max} (µm)	10.2				
T_c (min)	75				
L_m (g)	3.4				

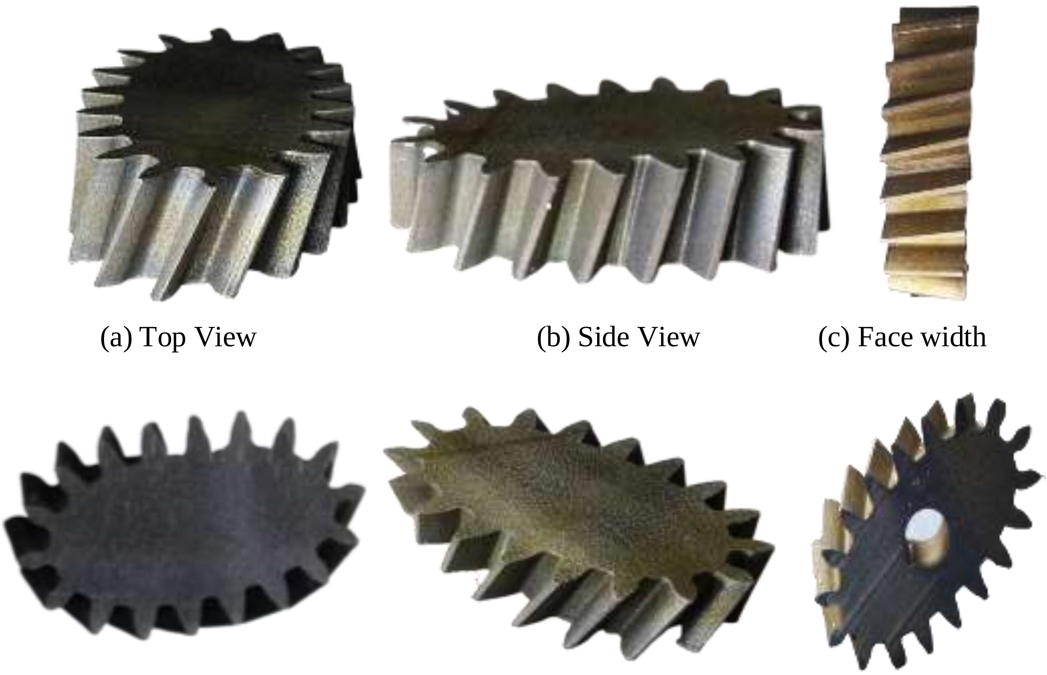
Table 4.5: Values of grey relational coefficients (GRC) and grey relational grades (GRG) for the considered responses for all the runs of the **Stage-2** experiments.

Experimental results				**Deviation sequence**				**Grey relational coefficient (GRC)**				**Grey relational grade (GRG)**
R_a	R_{max}	T_c	L_m	R_{max}	R_a	T_c	L_m	R_{max}	R_a	T_c	L_m	
1.13	8.15	65	3.43	0.000	0.019	0.000	0.368	1.000	0.964	1.000	0.576	0.885
1.3	9.8	67	3.56	0.279	0.331	0.056	0.425	0.642	0.602	0.900	0.540	0.671
1.4	8.34	69	3.54	0.443	0.055	0.111	0.417	0.530	0.901	0.818	0.545	0.699
1.63	10.53	94	2.59	0.820	0.469	0.806	0.000	0.379	0.516	0.383	1.000	0.569
1.28	8.78	99	3.52	0.246	0.138	0.944	0.408	0.670	0.784	0.346	0.551	0.588
1.23	12.09	101	4.87	0.164	0.764	1.000	1.000	0.753	0.396	0.333	0.333	0.454
1.74	10.53	85	3.67	1.000	0.469	0.556	0.474	0.333	0.516	0.474	0.514	0.459
1.35	12.76	88	3.65	0.361	0.890	0.639	0.465	0.581	0.360	0.439	0.518	0.474
1.33	8.87	84	3.86	0.328	0.155	0.528	0.557	0.604	0.763	0.486	0.473	0.582
1.2	8.29	71	3.68	0.115	0.045	0.167	0.478	0.813	0.917	0.750	0.511	0.748
1.31	9.84	71	3.8	0.295	0.338	0.167	0.531	0.629	0.596	0.750	0.485	0.615
1.28	8.63	74	3.75	0.246	0.110	0.250	0.509	0.670	0.820	0.667	0.496	0.663
1.19	9.1	78	3.66	0.098	0.198	0.361	0.469	0.836	0.716	0.581	0.516	0.662
1.35	8.05	80	3.63	0.361	0.000	0.417	0.456	0.581	1.000	0.545	0.523	0.662
1.44	10.37	76	3.67	0.508	0.439	0.306	0.474	0.496	0.533	0.621	0.514	0.541
1.68	13.34	81	3.6	0.902	1.000	0.444	0.443	0.357	0.333	0.529	0.530	0.437
1.54	9.43	79	3.62	0.672	0.261	0.389	0.452	0.427	0.657	0.563	0.525	0.543
1.53	10.02	80	3.61	0.656	0.372	0.417	0.447	0.433	0.573	0.545	0.528	0.520

4.3.3 Conclusions from the Stage-2 Experiments

Following conclusions can be drawn from Stage-2 experiments:

- To get minimum value of the R_{max}, the parameter setting should be that P_w and F_w on their higher levels, and T_w should be on its lower level.
- For minimum value of the R_a, the parameter setting should be that P_w and T_w on their lower levels, and S_c should be on its higher level.
- P_w should be on its high value and T_w, F_w and S_c should be on their lower values to minimize T_c.
- P_w, F_w and S_c should be on their lower values to get minimum value of L_m.
- To get minimum values of R_a, R_{max}, T_c and L_m together parameter setting values should be that P_w should be on its high value and T_w, F_w and S_c should be on their lower values.
- R_{max}, R_a, T_c and L_m are mainly influenced by T_w and L_m is mainly influenced by F_w.



(a) Top View (b) Side View (c) Face width

(d)Front View (e) 3-D View (f) Gear with hub

Fig. 4.4: Different views of the EHG manufactured using the GRA optimized WSEM process parameters.

4.4 Results of stage-3 Experiments and their Analysis

Table 4.7 represents results for 30 runs of Stage-3 experiments which were conducted using central composite design (CCD) approach of response surface methodology (RSM) to study influence of four electrical parameters of WSEM process (pulse-on time 'T_{on}', pulse-off time 'T_{off}', servo-voltage 'V_s', peak current 'I_p') on the considered responses by varying them at five level each and to identify their optimum values.

Table 4.7: Results of the **Stage-3** experiments for all the 30 experimental runs.

Std run	**Run**	***T*** T_{on} *(μs)*	T_{off} *(μs)*	V_s *(V)*	I_p *(A)*	R_a *(μm)*	R_{max} *(μm)*	T_c *(min)*	L_m *(g)*
22	1	1.5	44.5	38	1.5	1.54	10.11	61	3.39
30	2	1.5	44.5	22	1.5	1.61	11.6	57	3.33
21	3	1.5	44.5	6	1.5	1.82	11.03	63	3.29
6	4	1.8	41.5	30	0.5	1.55	12.58	58	3.38
12	5	1.8	47.5	14	2.5	1.84	10.28	67	3.46
23	6	1.5	44.5	22	0.5	1.49	9.57	85	3.52
26	7	1.5	44.5	22	1.5	1.6	11.82	49	3.28
18	8	2.1	44.5	22	1.5	1.72	12.16	48	3.5
8	9	1.8	47.5	30	0.5	1.63	11.13	69	3.56
9	10	1.2	41.5	14	2.5	1.75	11.99	72	3.3
14	11	1.8	41.5	30	2.5	1.56	11.7	61	3.5
24	12	1.5	44.5	22	2.5	1.59	10.49	85	3.46
3	13	1.2	47.5	14	0.5	1.45	9.92	86	3.4
2	14	1.8	41.5	14	0.5	1.45	11.71	75	3.44
4	15	1.8	47.5	14	0.5	1.62	10.87	90	3.59
19	16	1.5	38.5	22	1.5	1.44	12.71	49	3.31
5	17	1.2	41.5	30	0.5	1.54	9.61	70	3.3
13	18	1.2	41.5	30	2.5	1.46	10.43	92	3.49
7	19	1.2	47.5	30	0.5	1.44	9.66	85	3.41
25	20	1.5	44.5	22	1.5	1.55	11.21	56	3.35
15	21	1.2	47.5	30	2.5	1.22	9.88	89	3.43
20	22	1.5	50.5	22	1.5	1.21	10.72	71	3.44
10	23	1.8	41.5	14	2.5	1.79	12.2	55	3.45
27	24	1.5	44.5	22	1.5	1.57	11.23	54	3.31
29	25	1.5	44.5	22	1.5	1.61	11.26	55	3.32
17	26	0.9	44.5	22	1.5	1.3	9.5	89	3.35
1	27	1.2	41.5	14	0.5	1.4	9.52	70	3.2
16	28	1.8	47.5	30	2.5	1.52	10.57	49	3.37
28	29	1.5	44.5	22	1.5	1.62	11.22	57	3.26
11	30	1.2	47.5	14	2.5	1.54	11.43	81	3.33

4.4.1 Development of Response Surface Models

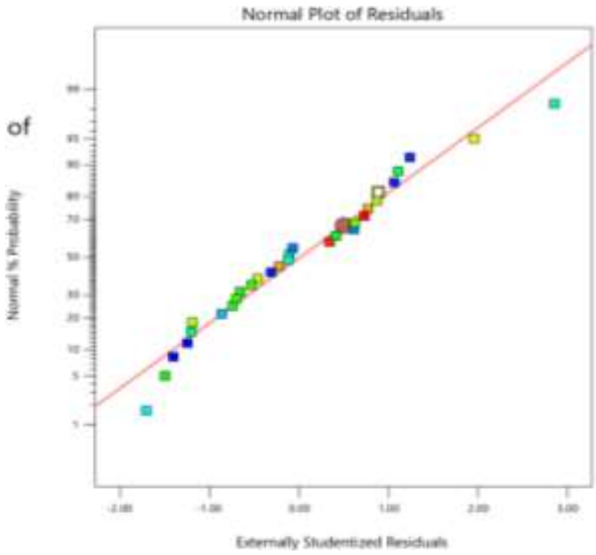
Response surface models were developed for the considered responses of maximum and average and surface roughness (R_{max} and R_a), EHG cutting time (T_c) and EHG material loss (L_m) using the results of the Stage-3 experiments (presented in Tables 4.7) using *Design Expert* software. Subsequently, analysis of variance (ANOVA) was used to determine significance of the developed response surface models, and significant WSEM parameters and their interactions in these models using 95% confidence interval. Results of ANOVA are presented in Appendix-B. The normal probability plots are depicted in Fig. 4.5 showing normal distribution of the data for the models. As a result of regression analysis, following equations were developed in terms of actual values of the considered responses:

$$R_{max}= 3.36104+ 20.39375\ T_{on} - 0.465625\ T_{off}+0.017253V_s+ 6.15\ I_p-0.325T_{on} * T_{off}+0.109375T_{on}*V_s-1.36667\ T_{on}*I_p - 0.048333\ T_{off}*I_p - 0.033437\ V_s*I_p-1.45139T_{on}^2-0.003057V_s^2-0.330625I_p^2 \quad (1)$$

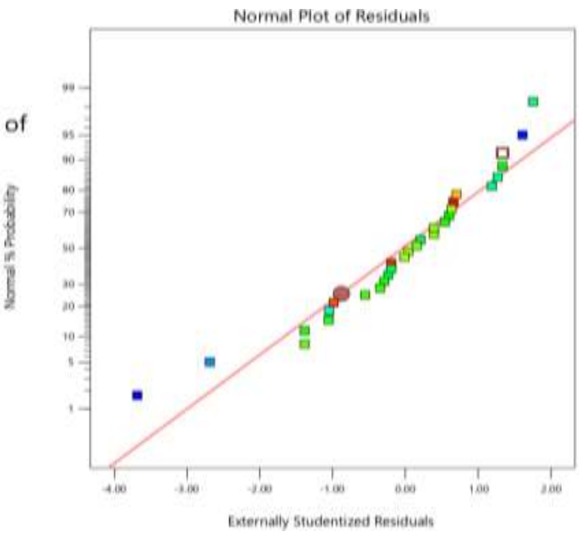
$$R_a=-10.44627 - 1.68681\ T_{on}+ 0.559491\ T_{off}+0.030091\ V_s +0.790417\ I_p+0.052778\ T_{on}*T_{off} -0.013333T_{off}*I_p - 0.010938\ V_s*I_p - 0.006829T_{off}^2+0.000426V_s^2 \quad (2)$$

$$T_c=307.50716 - 62.69097T_{on}- 13.51215\ T_{off}-2.00521\ T_{on}*V_s - 17.29167\ T_{on}*I_p-0.106771T_{off}*V_s1.0625T_{off}*I_p+0.429687V_s*I_p+46.18056T_{on}^2+0.225694T_{off}^2+0.039551V_s^2+8.28125I_p^2 \quad (3)$$

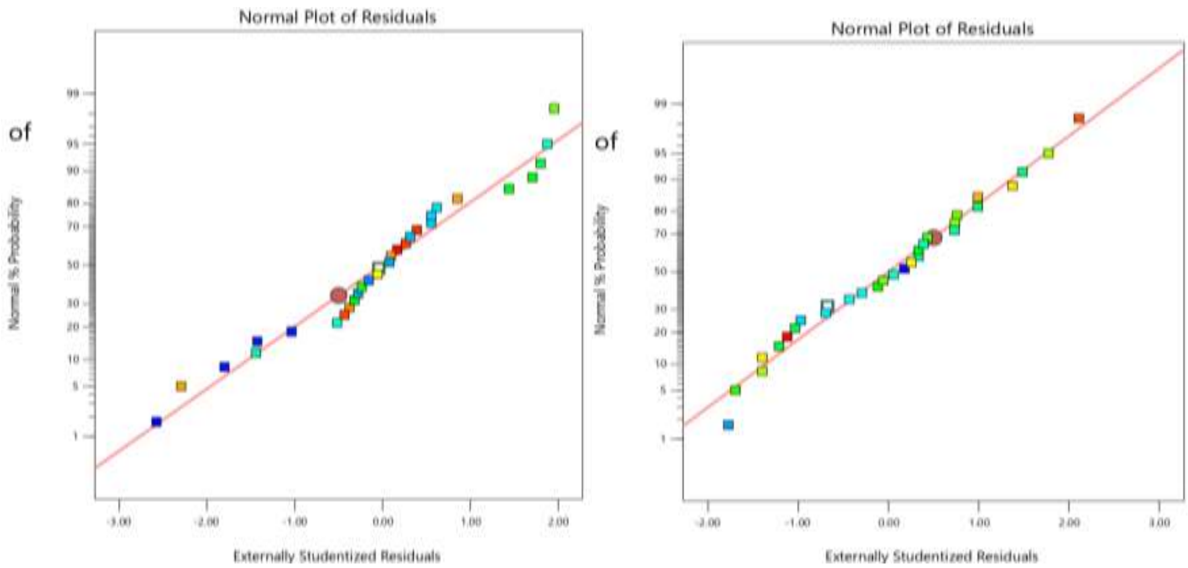
$$L_m = 4.58451-0.183854\ T_{on} -0.115075T_{off} + 0.047975\ V_s - 0.013802\ T_{on}*V_s-0.089583\ T_{on}*I_p - 0.000755\ T_{off}*V_s - 0.016458\ T_{off} *I_p+ 0.334491\ T_{on}^2 + 0.001956\ T_{off}^2 + 0.046354\ I_p \quad (4)$$



(a) R_{max}



(b) R_a



(c) T_c **(d) L_m**

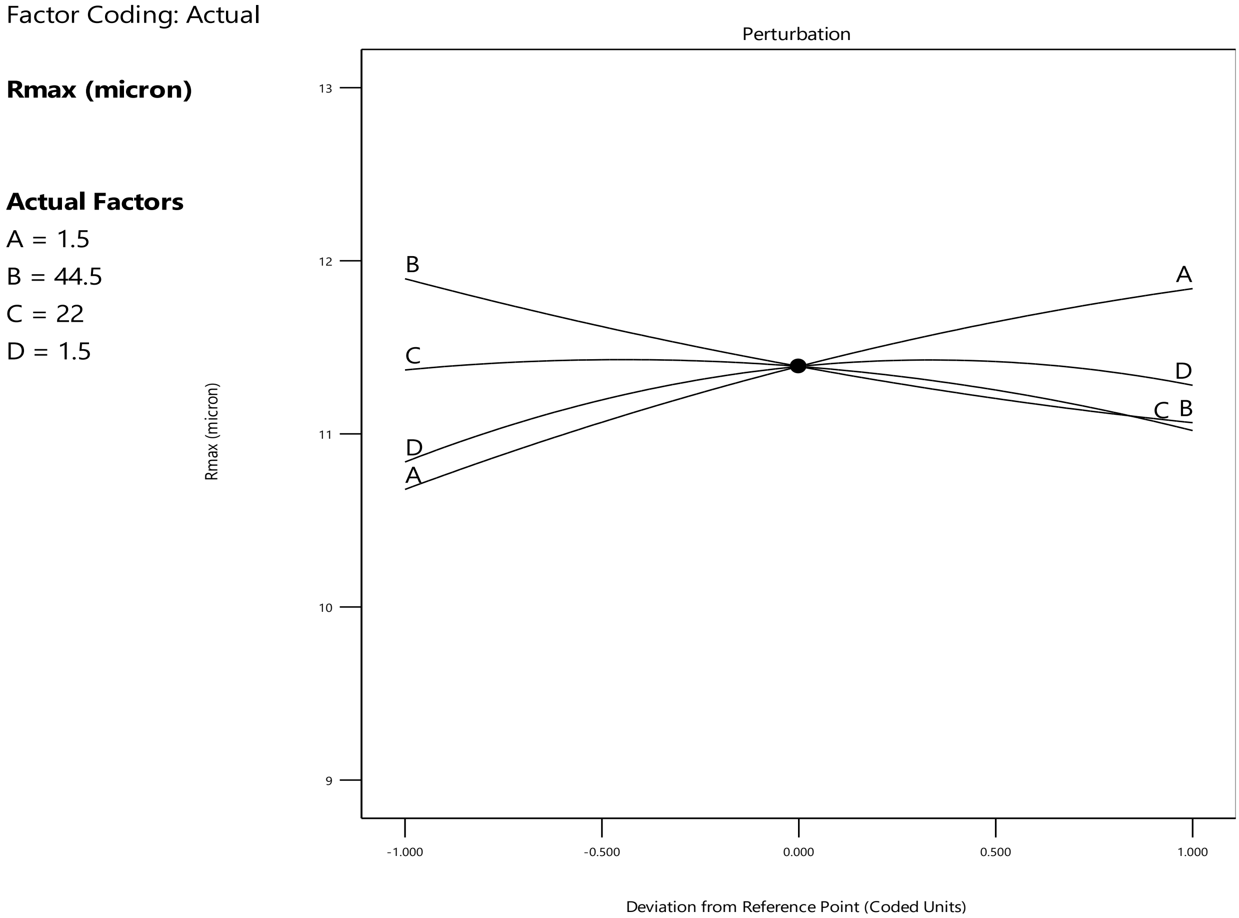
Fig. 4.5: Normal plots of the residuals for the considered responses.

4.4.2 Influence of the WSEM Parameters on the Responses

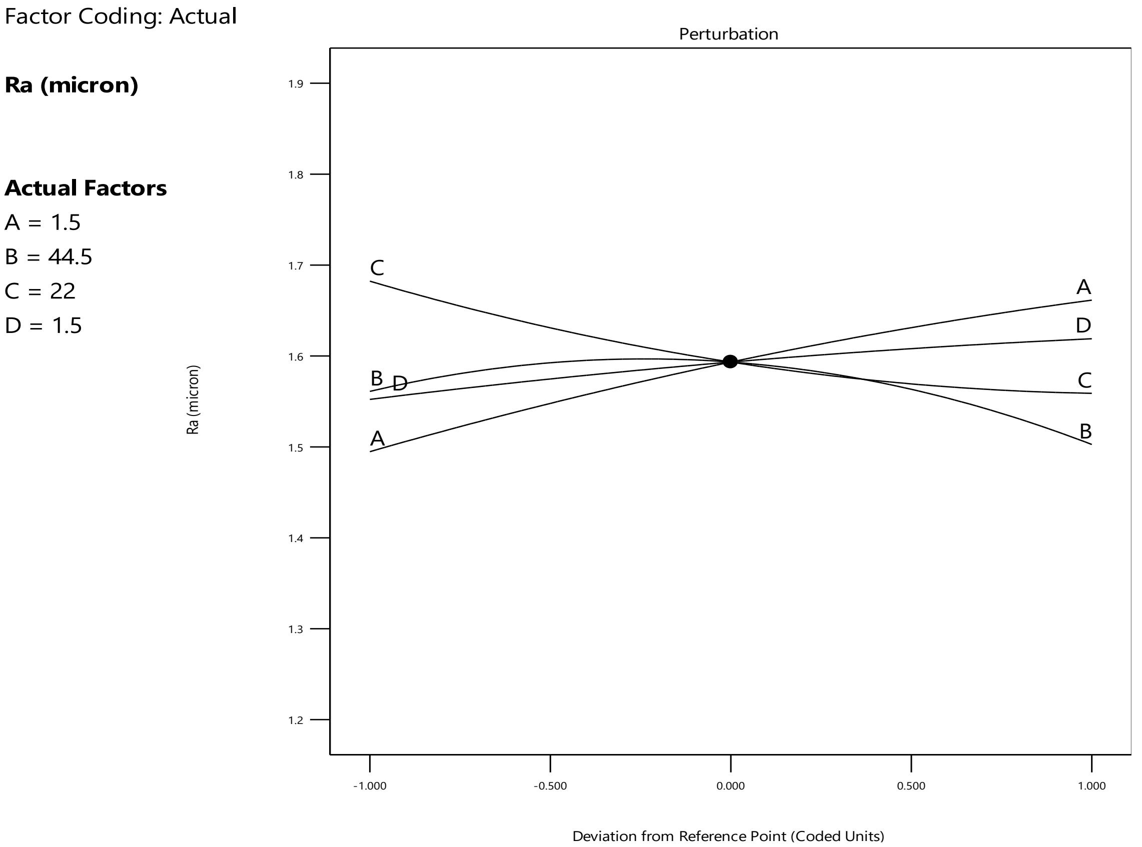
Figure 4.6 depicts influences of pulse-on time (T_{on}), pulse-off time (T_{off}), servo voltage (V_s), and peak current (I_p) on the R_{max}, R_a, T_c and L_m. It can be seen from these Figures that:

- Values of R_{max} and R_a increase with increase in pulse-on time (T_{on}) and peak current (I_p) and decreases with increase in pulse-off time (T_{off}) and servo voltage (V_s).
- Value of T_c increases with increase in pulse-off time (T_{off}) and decreases with decrease in the values of pulse-on time (T_{on}), and servo voltage (V_s). The value first decreases and then increases with the value of peak current (I_p).
- Value of L_m increases with increase in the value in pulse-on time (T_{on}), pulse-off time (T_{off}) and servo voltage (V_s). With increase in peak current (I_p), value of L_m first decreases and then increases.
- Value of T_c increases with increase in pulse-off time (T_{off}) and decreases with decrease in the values of pulse-on time (T_{on}), and servo voltage (V_s). The value first decreases and then increases with the value of peak current (I_p).
- Value of L_m increases with increase in the value in pulse-on time (T_{on}), pulse-off time (T_{off}) and servo voltage (V_s). With increase in peak current (I_p), value of L_m first decreases and then increases.

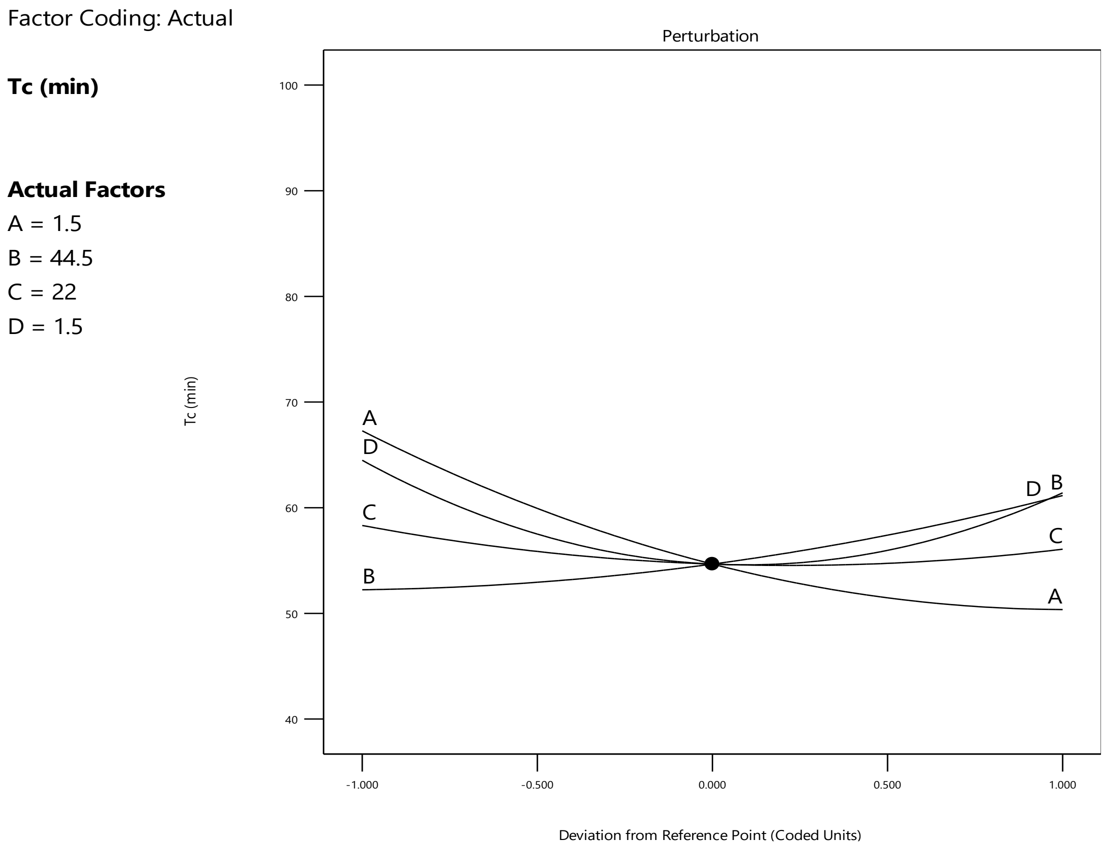
Table 4.8 presents the optimum values of four electrical parameters identified from graphs of Fig 4.6 along with values corresponding values of the responses.



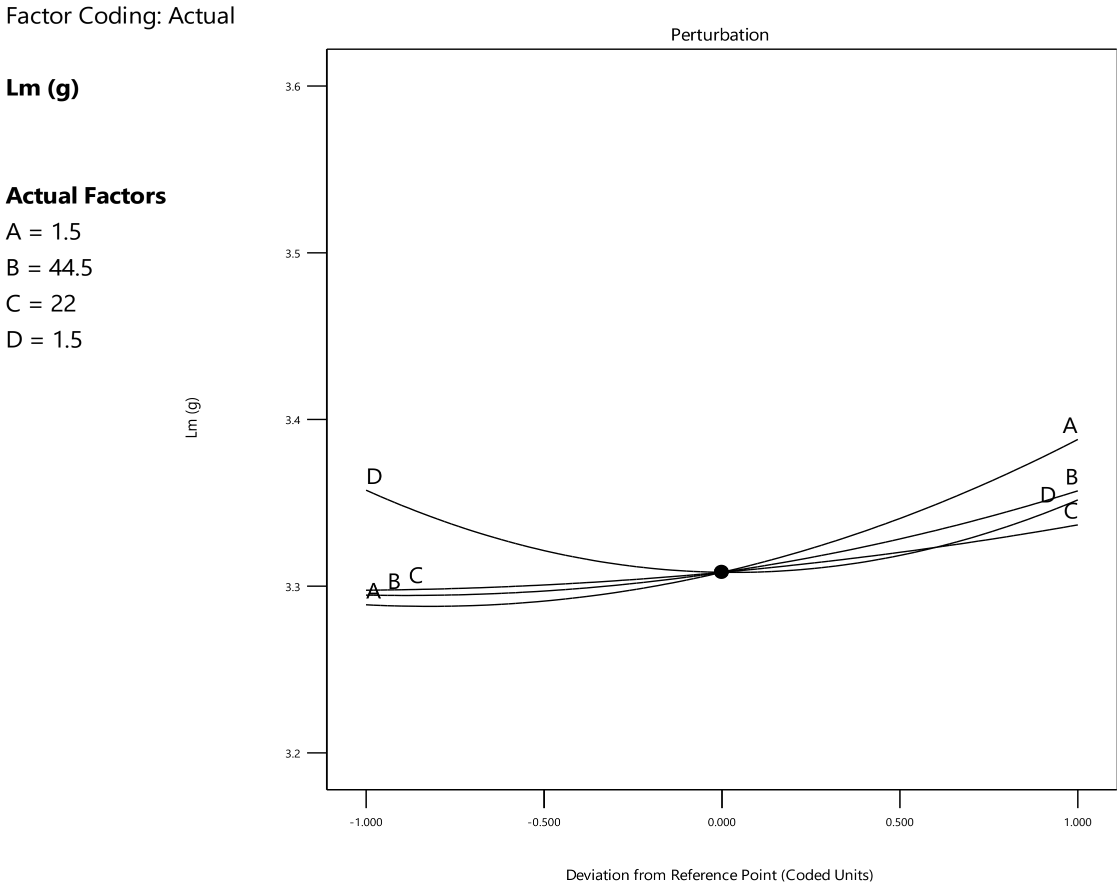
(a) Maximum roughness value of EHG flank surface (R_{max})



(b) Average roughness value of EHG flank surface (R_a)



(c) EHG cutting time (T_c)



(d) EHG material loss (L_m)

Fig. 4.6: Variation of the responses with electrical parameters of WSEM parameters.

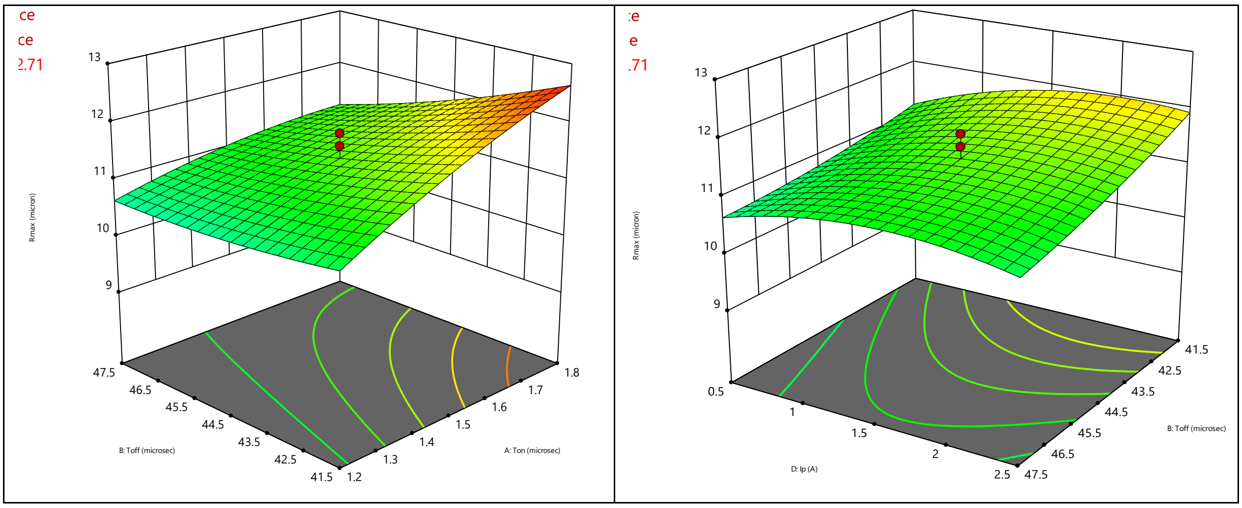
Table 4.8: Identified optimum values of the electrical parameters of WSEM and the responses from the **Stage-3** experiments.

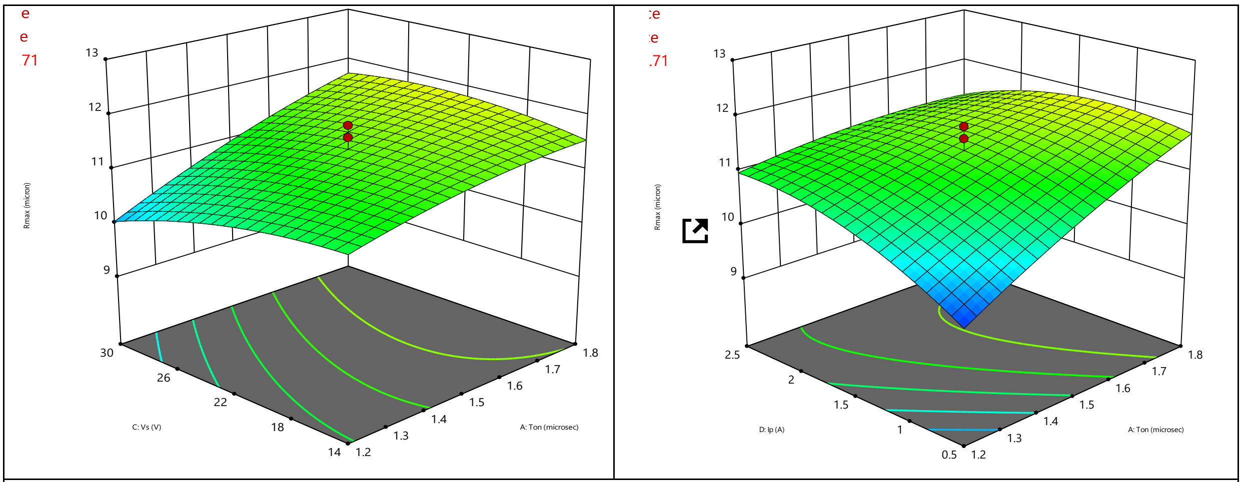
Response		**Electrical parameters of WSEM**			
Name	**Value**	***T_{on} (µs)***	***T_{off} (µs)***	***V_s (Volts)***	***I_p (A)***
R_a (µm)	1.21	1.5	50.5	22	1.5
R_{max} (µm)	9.5	0.9	44.5	22	1.5
T_c(min)	48	2.1	44.5	22	1.5
L_m (g)	3.2	1.2	41.5	14	0.5

4.4.3 Influence of Significant Interactions of WSEM Parameters

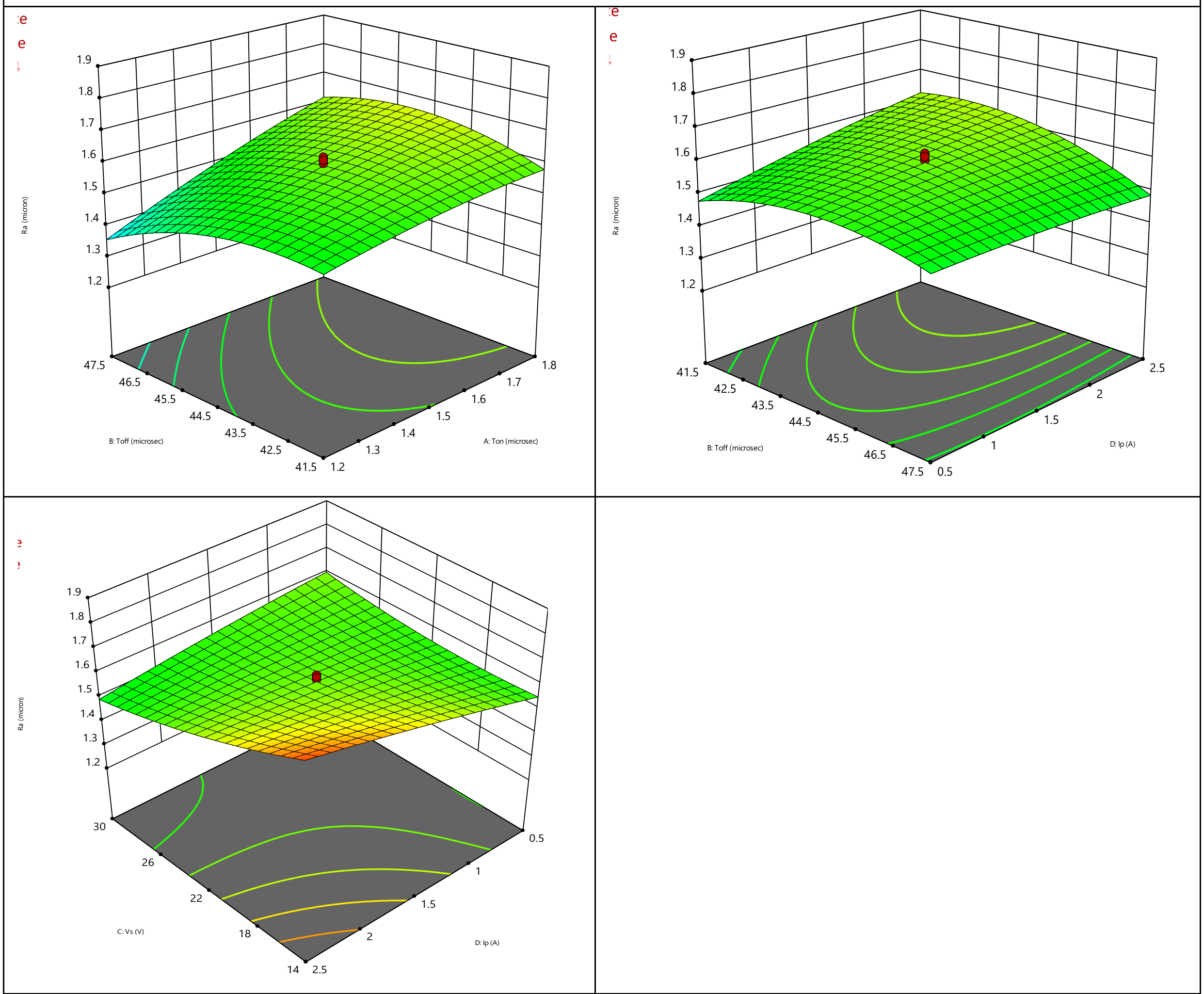
ANOVA was used to identify the significant interactions between the four electrical parameters of WSEM which affect the considered responses. Results of ANOVA are presented in Appendix-B. These interaction effects are plotted using values of the responses predicted by the response surface models and are presented in Fig.4.7. Following interactions were found to be significant different responses:

- **For R_{max}:** Interactions between T_{on} and T_{off}; T_{on} and V_s; T_{on} and I_p; T_{off} and I_p; $V_s$and I_p
- **For R_a**: Interactions between T_{on} and T_{off}; Ip and V_S; T_{off} and Ip; Vs and I_p
- **For T_c**: Interactions between T_{on} and V_S; T_{on} and I_p; T_{off} and V_s; T_{off} and I_p; V_s and I_p
- **For L_m:** Interactions between T_{on} and Vs; T_{off} and V_S; T_{on} and I_p; T_{off} and I_p

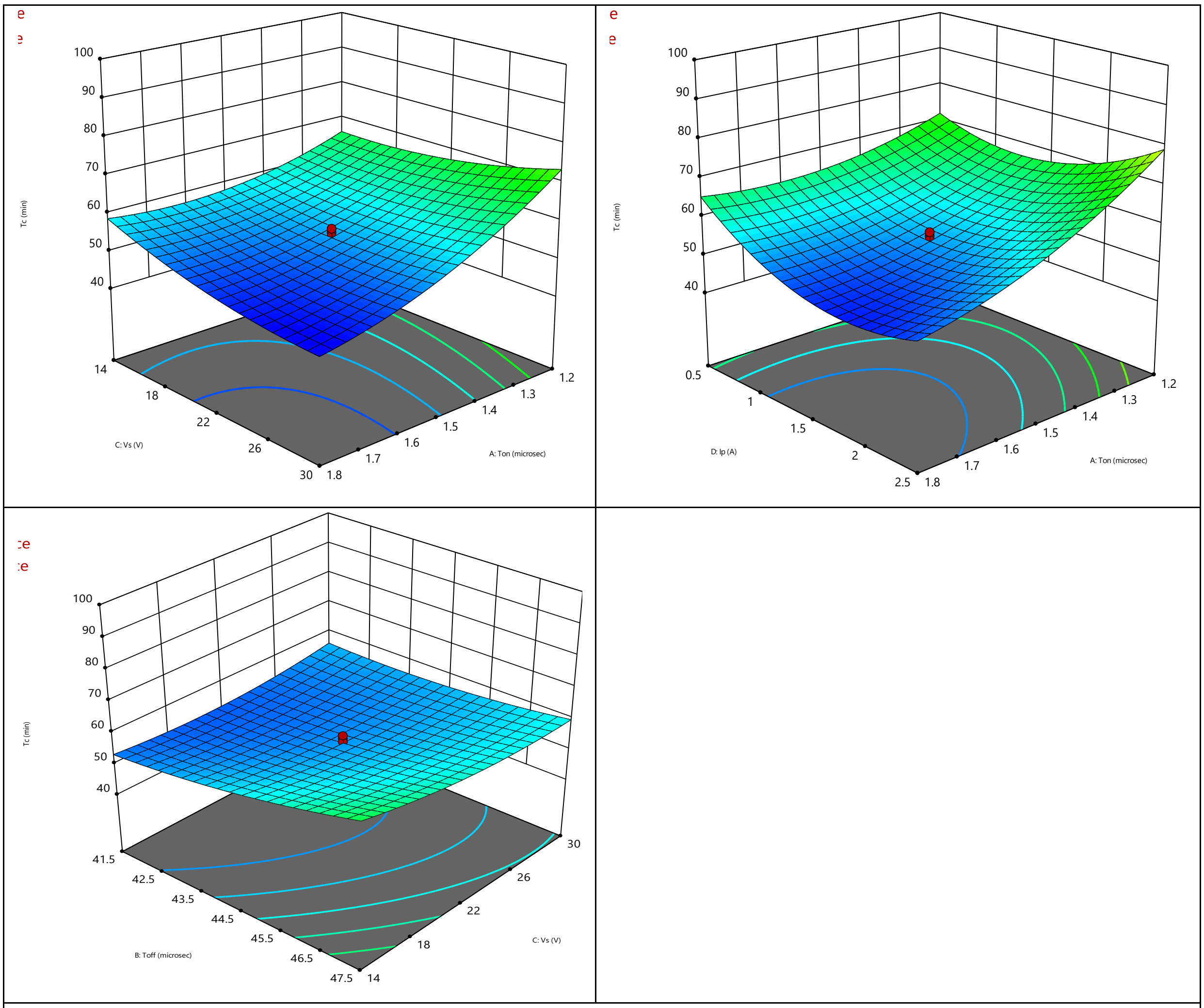




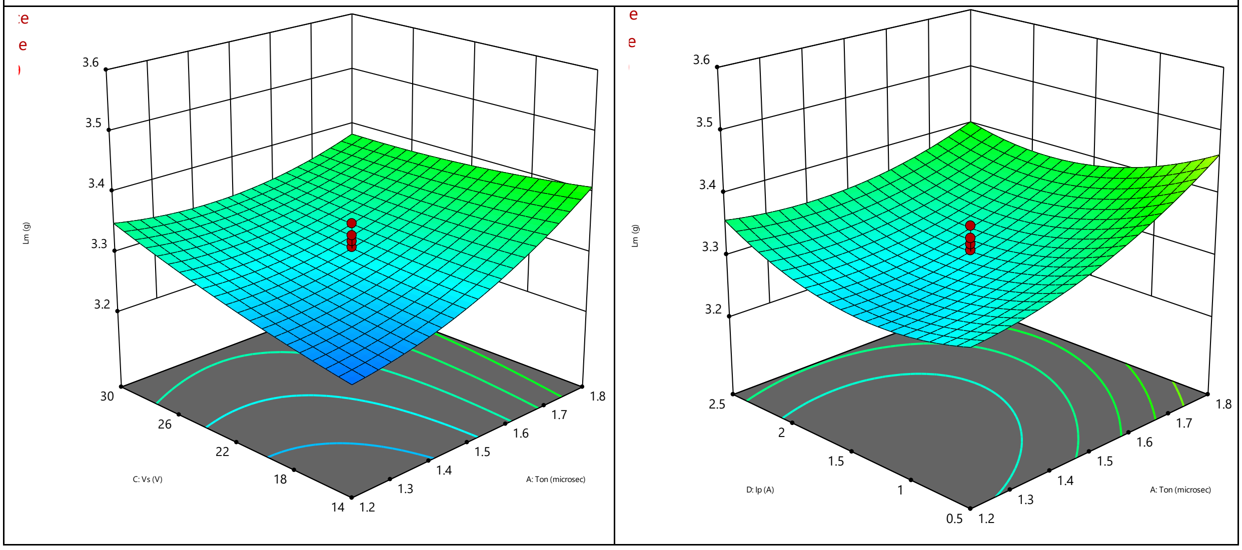
(a) For mximum roughness value of EHG flank surface (R_{max})

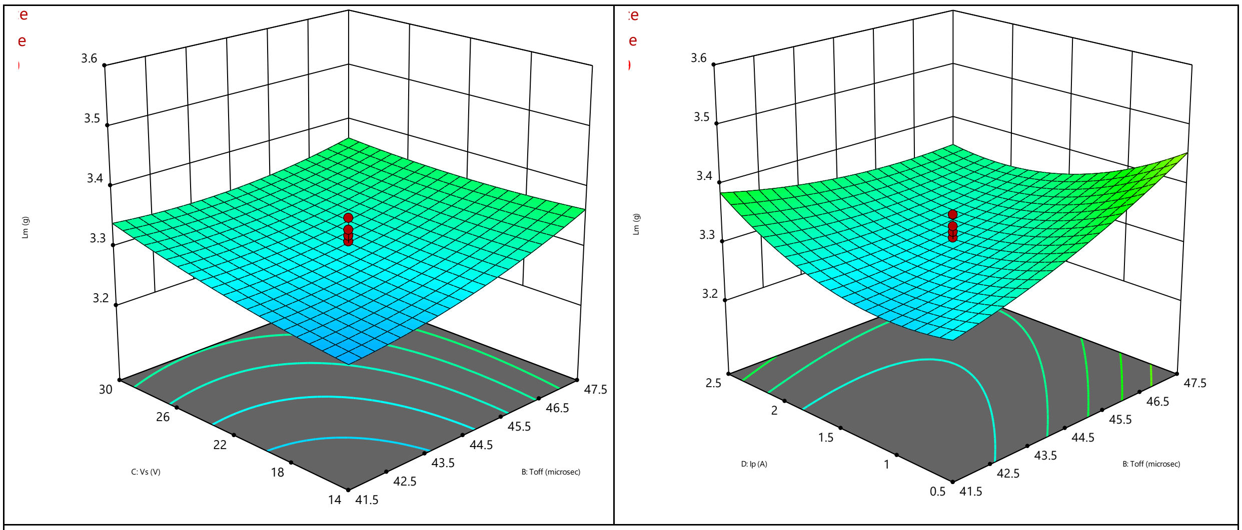


(b) For average roughness value of EHG flank surface (R_a)



(C) For EHG cutting time (T_c)





(d) For EHG material loss (L_m)

Fig. 4.7: Surface plots showing effects of the identified significant interactions on the considered responses during manufacturing of EHG by WSEM process.

It can be observed from these surface plots that minimum values of surface roughness parameters, EHG cutting time and EHG material loss can be achieved by following combinations:

- Lower values R_a can be achieved by using:
  (i) Lower values of T_{on} and higher values of T_{off}
  (ii) Lower values of I_p and higher values of T_{off}
  (iii) Higher values of I_p *and* higher values of V_s
- Lower values of R_{max} can be achieved by using:
  (i) Lower values of T_{on} and higher values of T_{off}
  (ii) Lower values of T_{on} and higher values of V_s
  (iii) Lower values of T_{on} and lower values of I_p
  (iv) Higher values of I_p and higher values of V_s
  (v) Higher values of T_{off} and lower values of I_p
- Lower values T_c can be achieved by using:
  (i) Higher values of T_{on} and higher values of V_s
  (ii) Higher values of I_p and higher values of T_{on}
  (iii) Lower values of T_{off} and higher values of V_s
  (iv) Lower values of I_p and lower values of T_{off}
- Lower values L_m can be achieved by using:
  (i) Lower values of T_{on} and lower values of I_p
  (ii) Lower values of T_{on} and lower values of V_s

(iii) Lower values of T_{off} and lower values of V_s

(iv) Lower values of T_{off} and lower values of I_p

4.4.4 Conclusions from the Stage-3 Experiments

Following major conclusions can be drawn from the analyses of the experimental observations of the Stage-3 experiments:

- Values of R_{max} and R_a increase with increase in pulse-on time (T_{on}) and peak current (I_p) and decreases with increase in pulse-off time (T_{off}) and servo voltage (V_s).
- Value of T_c increases with increase in pulse-off time (T_{off}) and decreases with decrease in the values of pulse-on time (T_{on}), and servo voltage (V_s). The value first decreases and then increases with the value of peak current (I_p).
- Value of L_m increases with increase in the value in pulse-on time (T_{on}), pulse-off time (T_{off}) and servo voltage (V_s). With increase in peak current (I_p), value of L_m first decreases and then increases.

4.5 Confirmation of the Optimization Results

Five validation experiments were conducted using those standard values available on the WSEM machine which are nearest to the identified optimum values of four electrical parameters during Statge-3 experiments to confirm the results of the optimization. Table 4.9 represents results of validation experiments. It can be seen from this table there is very good agreement between the values of the considered responses obtained from the optimization and their corresponding values obtained from the validation experiments.

Table 4.9: Results of the validation experimentsconducted to confirm optimization results for **Stage-3** experiments.

Nameand unit of WSEM parameters	**Values**	**Results of optimization**	**From validation experiment**
Pulse-on time (µs)	1.2	R_{max} =1.43 µm	R_{max} =1.3 µm
Pulse-off time (µs)	41.5	R_a = 9.77 µm	R_a = 9.88µm
Peak current (A)	0.5	T_c = 65 min	T_c = 68 min
Servo voltage (Volts)	14	L_m = 3.2 g	L_m = 3.2 g
Wire tension (g)	660		
Wire feed rate (m/min)	5		
Cutting speed overwrite (%)	60		
Dielectric pressure (kg/cm^2)	15		

4.6 Investigations on the Best quality EHG

The EHG manufactured using the optimized values of all WSEM process parameters is the best quality EHG because it minimized all the considered responses with respect to all the considered parameters. Table 4.10 presents details of parameters and responses for the best quality EHG manufactured by WSEM process. Further investigations on its flank surface topography, recast layer HAZ performed which is described in the following subsections.

Table 4.10: Values of WSEM parameters and the responses for the best quality EHG.

Nameand unit of WSEM parameters	**Values used in confirmation experiments**			
	For R_{max}	***For R_a***	***For T_c***	***For L_m***
Pulse-on time (µs)	1.2	1.2	1.7	1.2
Pulse-off time (µs)	46.5	47.5	42.5	41.5
Peak current (A)	1	2.5	1.5	1
Servo voltage (Volts)	30	30	27	14
Wire tension (g)	660	660	660	660
Wire feed rate (m/min)	5	5	5	5
Cutting speed overwrite (%)	60	60	60	60
Dielectric pressure (kg/cm²)	15	15	15	15
Value by optimization	*9.46*	*1.20*	*47.9*	*3.19*
Value by experiment	*9.5*	*1.21*	*48*	*3.2*

4.6.1 Flank Surface Topography

Flank surface topography of the best quality EHG manufactured by WSEM process was examined using field emission scanning electron microscope (FESEM). It can be seen from the FESEM images presented in Fig. 4.8 that the flank surface was free from chips,oil, foreign matter and other unwanted particles. Recast material was present on the surface which makes the surface uneven to some extent.

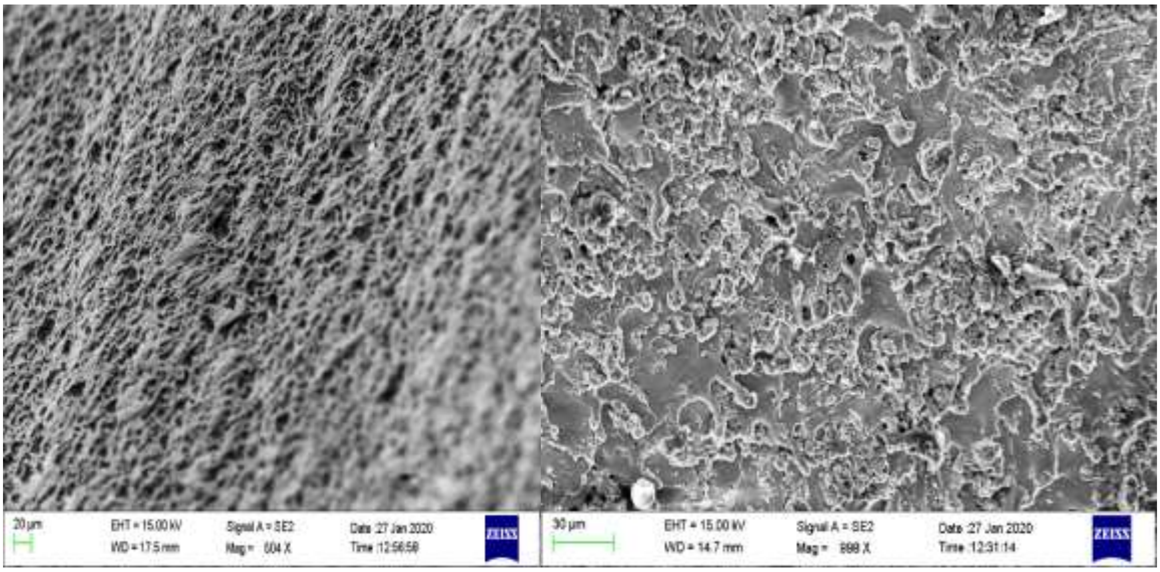


Fig. 4.8: Topography of flank surface of the best quality EHG manufactured by WSEM.

4.6.2 Surface Roughness

The EHG manufactured by WSEM process, after optimization of the process parameters had minimum values of maximum surface roughness as 7.8 µm and average surface roughness as 1.12 µm.

4.6.3 Tooth profile

Figure 4.9 depicts the tooth profile of the best quality EHG manufactured by WSEM process. It can be seen from the enlarged images of teeth that the gear has uniform, accurate and undamaged tooth profile and flank surfaces without any undercut at root and also are free from burrs and sharp edges.

4.6.4 Recast Layer

The recast layer and heat affected zone can be easily seen in the Fig. 4.10. Thickness of the recast layer and HAZ were measured. The average thickness of the recast layer was 8.177 µm and average thickness of the HAZ was 21.46 µm**.**

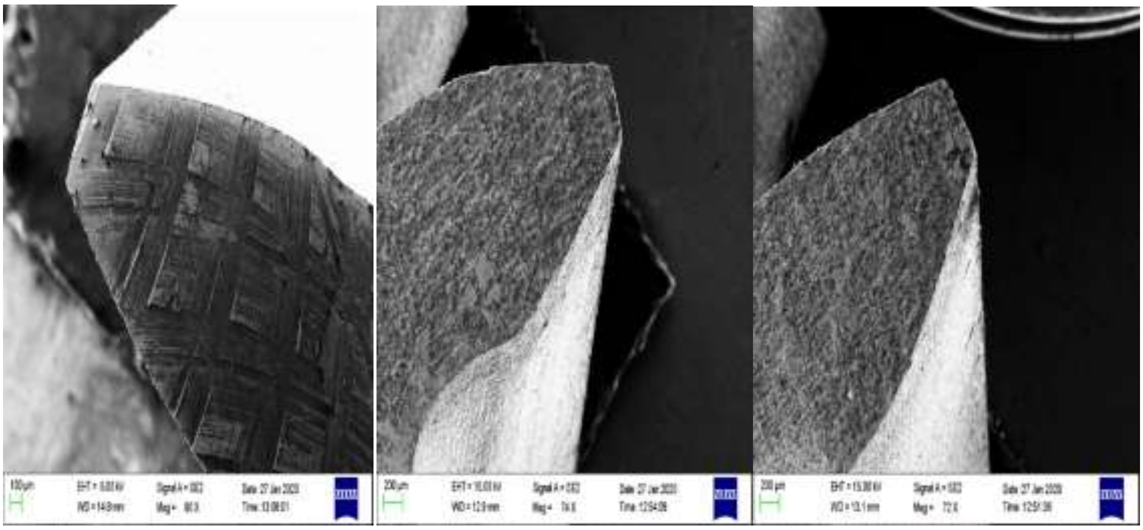


Fig: 4.9: Tooth profile of the best quality EHG manufactured by WSEM process.

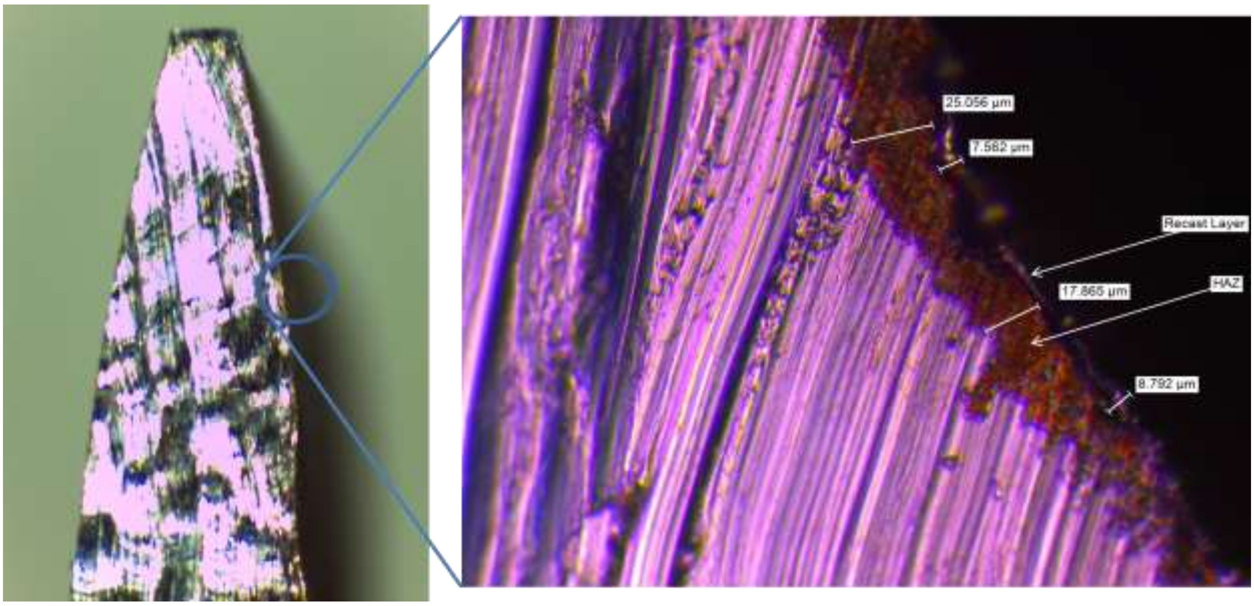


Fig 4.10: Heat affected zone (HAZ) and recast layer on tooth flank surface of the best quality EHG manufactured by WSEM process.

4.7 Arrangement for Meshing of the EHG

An apparatus was developed to confirm meshing of the manufactured EHG. For this both right hand EHG and left-hand EHG were required. Left hand EHG was programmed using the same specifications and manufactured using the same WSEM process parameters. Figure 4.11 shows thedeveloped apparatus. Following are its details:

- Outer body of the apparatus was made by clear acrylic for easy internal visibility and to protect the arrangement.
- The outer body was made as detachable to perform maintenance work if required.
- Aluminum plate was used for mounting and supporting of the shafts of the EHG.
- Both the gear shafts were attached with the gears from one end. One shaft was attached to the motor to the other end and another shaft was left free to rotate to the other end.
- A 9-volts battery was used to supply power to the motor.
- Power on/off switch was attached, electrical connections were made.
- Fixing of the aluminum plate, motor and battery was done.
- Assembling of motor shaft, gear shaft and the gears were done.

As the power is switched on, both the gears started rolling and proper meshing was observed. No slip, disengagement and uneven rotation were observed. The test performed many times and found successful engagement of the gear teeth. The gears were allowed to transmit power for 10 minutes in every test.

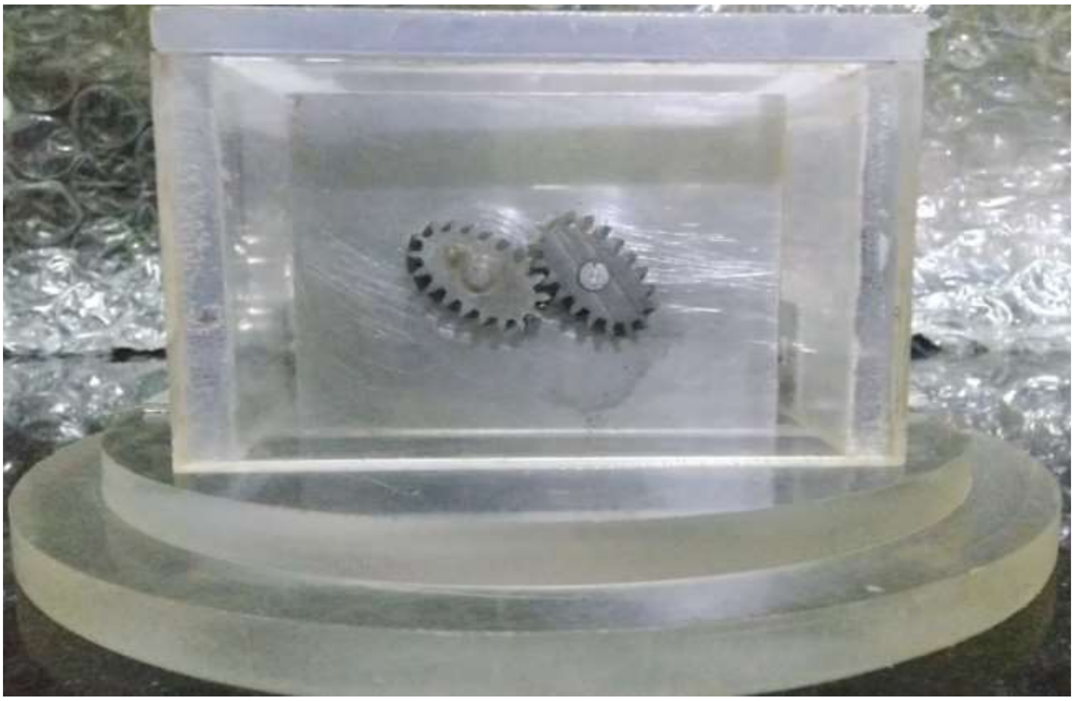


Fig 4.11: Apparatus for checking meshing of the EHG manufactured by WSEM process.

Chapter 5

Conclusions and Scope for the Future Work

The significant achievements of the present research work, conclusions drawn from it, and scope for future work are summarized in this chapter.

5.1 Significant Achievements

As per the literature available, this was the first attempt to manufacture EHG using WSEM process and investigations on flank surface roughness, gear cutting time and gear material loss. Following are significant achievements of the present research work:

- Explored WSEM process for manufacturing of different types of NCG in meso and macro sizes.
- Studied influences of four non-electrical and four electrical parameters of WSEM process parameters and their significant interactions on surface roughness parameters, gear cutting time and gear material loss during manufacturing of EHG from SS 304 through various stages of experimentation.
- Identified optimum values of four non-electrical parameters of WSEM process by grey relational analysis and four electrical parameters by RSM for manufacturing of EHG and confirmed the optimized values through validation experiments.
- Developed of response surface models of the considered responses in terms of four electrical parameters of WSEM.
- Examined surface topography, studied HAZ and recast layer for the EHG manufactured using the eight optimized parameters of WSEM process.
- Developed arrangement for checking meshing of the manufactured EHG.

5.2 Conclusions

Following conclusions can be drawn from the present research work:

- WSEM is a suitable process of NCG manufacturing. The process is non-toxic, clean, user friendly, flexible and an easy process of NCG manufacturing.
- WSEM process is capable to manufacture NCEH, NCBG and NCBHG of different types.
- The EHG manufactured by the WSEM process are of good surface finish, in less cutting time and with minimum material loss. The process can be easily adopted by industries for mass production of EHG.
- To get minimum value of the R_{max}, the parameter setting should be that P_w and F_w on

their higher levels, and T_w should be on its lower level.

- For minimum value of the R_a, the parameter setting should be that P_w and T_w on their lower levels, and S_c should be on its higher level.
- P_w should be on its high value and T_w, F_w and S_c should be on their lower values to minimize T_c.
- P_w, F_w and S_c should be on their lower values to get minimum value of L_m.
- To get minimum values of R_a, R_{max}, T_c and L_m together parameter setting values should be that P_w should be on its high value and T_w, F_w and S_c should be on their lower values.
- R_{max}, R_a, T_c and L_m are mainly influenced by T_w and L_m is mainly influenced by F_w.
- The values of R_{max} and R_a increase with increase in pulse-on time (T_{on}) and peak current (I_p) and decreases with increase in pulse-off time (T_{off}) and servo voltage (V_s).
- The value of T_c increases with increase in pulse-off time (T_{off}) and decreases with decrease in the values of pulse-on time (T_{on}), and servo voltage (V_s). The value first decreases and then increases with the value of peak current (I_p).
- The value of L_m increases with increase in the value in pulse-on time (T_{on}), pulse-off time (T_{off}) and servo voltage (V_s). With increase in peak current (I_p), value of L_m first decreases and then increases.
- Recast layer and heat affected zone was appeared on the machined surfaces.
- Because of the recast layer formation irregular shaped craters are formed on the surfaces.
- Shape of the teeth of the EHG are uniform, accurate, no undercutting at the root and no sharp edges were present.
- Topography examination of flank surfaces of the best quality EHG had shown clean surface free from burrs, cracks, nicks,asperities and without any foreign matter attached on it.

5.3 Scope for the Future Work

The present work was aimed to establish WSEM process as an easy and effective process of near net-shape manufacturing of high quality EHG. It was the first attempt to manufacture NCG with helical teeth, therefore there is lot of scope for the future research work which may include:

- Investigations on manufacturing of different types of NCG using small size wire and by using wire made of different materials.
- Investigations on manufacturing of different types of NCG, NCHG, NCBG, NCBHG,

internal NCG, internal helical NCG by WSEM process.

- Investigations on manufacturing of different types of NCG, NCHG, NCBG, NCBHG, internal NCG, internal helical NCG in meso and micro shape by WSEM process.
- Investigations on manufacturing of different types of NCG, NCHG, NCBG, NCBHG, internal NCG, and internal helical NCG made of other gear materials by WSEM process.
- Investigations on measurements of microgeometry related parameters such as lead, profile and runout for NCG.
- Investigation on macro-geometry, wear characteristic and residual of different types of NCG.

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Appendix-A

Details of the Measuring Instruments Used

3D Surface Roughness cum Contour Tracer (Gear Research LAB, IIT Indore)

Make	Mahr GmbH, Germany
Model	MarSurf LD 130
Resolution	0.8 nm
Start of traversing length	0.1 mm
End of traversing length (in X)	130 mm
Traverse length	0.1 mm - 130 mm
Positioning speed	0.02 mm/s to 200 mm/s; 0.02 mm/s to 10 mm/s;
Measuring range (mm)	13 mm (100 mm probe arm) 26 mm (200 mm probe arm)
Measuring force	0.5 mN to 30 mN, software-adjustable

Figure A1: 3D Surface roughness-cum-contour tracing equipment.

Details of Scanning Electron Microscope

(Sophisticated Instrument Centre, IIT Indore)

Make	Carl Zeiss NTS GmbH, Germany
Model	SUPRA 55
Resolution	1.0 nm @ 15 kV; 1.7 nm @ 1kV; 4.0 nm @ 0.1 kV
Acceleration Voltage	0.1 - 30 kV
Magnification	12x - 900,000x
Stages	5-axes motorized eccentric specimen stage X = 130 mm; Y = 130 mm; Z = 50 mm; T = 70±3°; R = 360° (continuous)
Standard detectors	Everhart-Thornley secondary electron detector
Efficiency in-lens detector	High

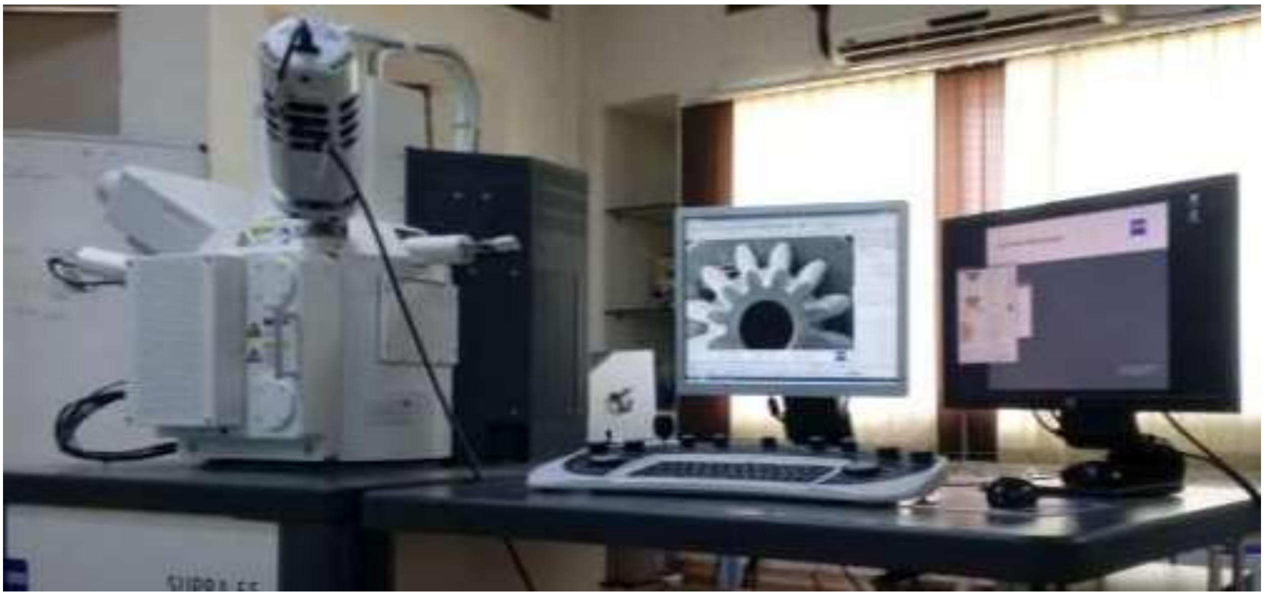

Figure A2: Field emission scanning electron microscope.

- **Details of the Inverted Optical Microscope**

(Gear Research Lab, IITIndore)

Model	Leica DM2500M
Power supply	Stabilized universal power supply unit 90–230 V for 12 V 30W
Magnifying Range	10X, 100X
Software	Leica “QMW” for image analysis
Image Analysis	Digital
Attachment	Polariser

Figure A3: Optical Microscope

Appendix-B

ANOVA for Quadratic Models of the Considered Responses

ANOVA table for Maximum Surface Roughness (R_{max})

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	25.29	14	1.81	26.26	< 0.0001	significant
A-Ton	8.07	1	8.07	117.39	< 0.0001	
B-Toff	4.15	1	4.15	60.34	< 0.0001	
C-Vs	0.7350	1	0.7350	10.69	0.0052	
D-Ip	1.18	1	1.18	17.15	0.0009	
AB	1.37	1	1.37	19.90	0.0005	
AC	1.10	1	1.10	16.03	0.0012	
AD	2.69	1	2.69	39.11	< 0.0001	
BC	0.0016	1	0.0016	0.0233	0.8808	
BD	0.3364	1	0.3364	4.89	0.0429	
CD	1.14	1	1.14	16.65	0.0010	
A^2	0.4680	1	0.4680	6.80	0.0198	
B^2	0.2253	1	0.2253	3.28	0.0904	
C^2	1.05	1	1.05	15.26	0.0014	
D^2	3.00	1	3.00	43.60	< 0.0001	
Residual	1.03	15	0.0688			
Lack of Fit	0.6988	10	0.0699	1.05	0.5107	not significant
Pure Error	0.3328	5	0.0666			
Cor Total	26.32	29				

ANOVA table for the Average Surface Roughness (R_a)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.6474	14	0.0462	22.71	< 0.0001	significant
A-Ton	0.1667	1	0.1667	81.86	< 0.0001	
B-Toff	0.0204	1	0.0204	10.03	0.0064	
C-Vs	0.0913	1	0.0913	44.82	< 0.0001	
D-Ip	0.0267	1	0.0267	13.10	0.0025	
AB	0.0361	1	0.0361	17.73	0.0008	
AC	0.0001	1	0.0001	0.0491	0.8276	
AD	0.0064	1	0.0064	3.14	0.0965	
BC	0.0081	1	0.0081	3.98	0.0646	
BD	0.0256	1	0.0256	12.57	0.0029	
CD	0.1225	1	0.1225	60.16	< 0.0001	
A^2	0.0063	1	0.0063	3.12	0.0979	
B^2	0.1036	1	0.1036	50.88	< 0.0001	
C^2	0.0204	1	0.0204	10.03	0.0064	
D^2	0.0016	1	0.0016	0.8004	0.3851	
Residual	0.0305	15	0.0020			
Lack of Fit	0.0268	10	0.0027	3.59	0.0855	not significant
Pure Error	0.0037	5	0.0007			
Cor Total	0.6779	29				

ANOVA table for Gear Cutting Time (T_c)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	5706.45	14	407.60	20.15	< 0.0001	significant
A-Ton	1717.04	1	1717.04	84.89	< 0.0001	
B-Toff	477.04	1	477.04	23.58	0.0002	
C-Vs	30.38	1	30.38	1.50	0.2393	
D-Ip	57.04	1	57.04	2.82	0.1138	
AB	7.56	1	7.56	0.3739	0.5501	
AC	370.56	1	370.56	18.32	0.0007	
AD	430.56	1	430.56	21.29	0.0003	
BC	105.06	1	105.06	5.19	0.0377	
BD	162.56	1	162.56	8.04	0.0125	
CD	189.06	1	189.06	9.35	0.0080	
A^2	473.81	1	473.81	23.42	0.0002	
B^2	113.17	1	113.17	5.59	0.0319	
C^2	175.74	1	175.74	8.69	0.0100	
D^2	1881.03	1	1881.03	92.99	< 0.0001	
Residual	303.42	15	20.23			
Lack of Fit	258.08	10	25.81	2.85	0.1299	not significant
Pure Error	45.33	5	9.07			
Cor Total	6009.87	29				

ANOVA table for EHG material loss (L_m)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.2451	14	0.0175	17.21	< 0.0001	significant
A-Ton	0.0590	1	0.0590	58.01	< 0.0001	
B-Toff	0.0234	1	0.0234	23.04	0.0002	
C-Vs	0.0092	1	0.0092	9.05	0.0088	
D-Ip	0.0002	1	0.0002	0.2007	0.6606	
AB	0.0003	1	0.0003	0.3011	0.5913	
AC	0.0176	1	0.0176	17.26	0.0008	
AD	0.0116	1	0.0116	11.36	0.0042	
BC	0.0053	1	0.0053	5.17	0.0381	
BD	0.0390	1	0.0390	38.35	< 0.0001	
CD	0.0033	1	0.0033	3.25	0.0915	
A^2	0.0249	1	0.0249	24.44	0.0002	
B^2	0.0085	1	0.0085	8.36	0.0112	
C^2	0.0022	1	0.0022	2.11	0.1666	
D^2	0.0589	1	0.0589	57.94	< 0.0001	
Residual	0.0153	15	0.0010			
Lack of Fit	0.0098	10	0.0010	0.8913	0.5917	Insignificant
Pure Error	0.0055	5	0.0011			
Cor Total	0.2604	29				