Experimental Investigations on Manufacturing of High Quality Miniature Gears by Wire Electric Discharge Machining

A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree

of

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Experimental Investigations on Manufacturing of High Quality Miniature Gears by Wire Electric Discharge Machining,** in the partial fulfillment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY** and submitted in the **DISCIPLINE OF MECHANICAL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2011 to November 2013 under the supervision of **Dr. N. K. Jain**, Associate Professor, Discipline of Mechanical Engineering.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

13-11-13

(Kapil Gupta)

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

13 Nov. 2013

(Dr. Neelesh Kumar Jain)

Kapil Gupta has successfully given his Ph.D. Oral Examination held on 3rd March 2014

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SYNOPSIS

With increasing emphasis on the miniaturization of various products used for scientific, industrial and domestic applications, the demand for manufacturing high quality fine-pitched miniature gears is growing continuously. Gears having outside diameter less than 10 mm are known as miniature gears. They can be further classified as *micro-gears* (outside diameter less than 1 mm) and *meso-gears* (outside diameter in the range of 1-10 mm). Miniature gears are one of the key components of the precise and accurate miniaturized devices used in the measuring instruments, timer mechanisms, micro and nano electromechanical systems (MEMS and NEMS), electronic and home appliances, miniature motors and pumps, automotive parts, business machines etc. Functional characteristics of these devices largely depend on the quality of the miniature gears used, thus necessitating the use of a precisely controlled process for manufacturing them. Brass, bronze, aluminium, stainless steel are the most commonly used materials for the miniature gears. Miniature brass gears are primarily used for motion transmission. These are fine-pitched gears and run at very high speed. Consequently, minimum running noise, accurate motion transfer, and longer service life are the important desirable characteristics for these gears.

Deutsche Normen (DIN) and *American Gear Manufacturers Association* (*AGMA*) have set international standards which define the quality of gears on the basis of amount of error or deviation in their micro-geometry (i.e. profile, lead, pitch and runout). DIN standard values range from 1-12 while, AGMA values range from 1-15. Lower DIN number or higher AGMA number indicates better quality of a gear and vice-versa. Table 1 presents the quality requirements of the gears for various applications in terms of DIN and AGMA numbers. The conventional processes for manufacturing the meso-gears include hobbing, stamping, extrusion, die casting and powder metallurgy. However, these processes suffer from some inherent limitations and moreover produce gears of low quality i.e. *DIN* number in the range of 9-12 or *AGMA* number in the range of 4-8 (Table 1). These limitations necessitate the exploration of an alternative process capable of manufacturing high quality meso-gears. The present research work is aimed at exploring wire electric discharge machining (WEDM) for manufacturing the high quality meso-gears and optimizing its performance through experimental investigations.

Table 1: Quality requirements of the gears for various applications and corresponding manufacturing processes.

Application type	Typical examples	AGMA quality number	DIN quality number	Corresponding manufacturing or finishing process
Commercial applications	Hand tools, Pumps, Clocks, Slow speed machineries, Various appliances	3		Plaster-mold casting, Permanent-mold casting
		4	12	Investment casting, Injection molding, *Extrusion**
		5	11	*Die casting**
		6	10	Milling, Cold drawing, *Stamping**, *Powder metallurgy**
		7		Rolling, Broaching
Precision applications	Aircraft engines, Turbines, Cameras, Automatic transmission systems, Instruments, High speed machineries	8	9-10	Rolling, Shaping, *Hobbing**
		9	8-9	Rolling, Shaving, Honing, Lapping, Grinding
		10	7-8	Shaving, Honing, Lapping, Grinding
		11	6-7	Shaving, Grinding
		12-13	4-6	Grinding
Ultra-precision applications	Precision instruments, Military navigations	14	3-4	Grinding
		15	1-2	Grinding with extra care

*Used for manufacturing of metallic *meso-gears*

The functional performance, motion transmission characteristics and service life of a gear mainly depend on its macro-geometry, micro-geometry, and surface quality. The errors in micro-geometry of gears are broadly classified in two groups, namely *form errors* and *location errors* as shown in Fig. 1. *Form errors* are the deviations from the intended nominal shape of the gear tooth surface. These are broadly spaced surface irregularities of lower frequency and longer wavelength. *Profile errors* and *lead errors* are the two important *form errors*. *Total profile error* is the deviation in the form and slope (angle) of actual tooth profile from the theoretical involute profile of the gear tooth. Profile error in a gear causes generation of noise while, the lead error determines its load carrying ability. *Location errors* represent the accuracy of location of teeth on a gear. These errors describe the angular and radial arrangement of teeth around the gear. *Pitch errors* and *runout* are the two important location errors. *Accumulated pitch error* is defined as the difference between the theoretical summation of pitch and summation of actual pitch measurements over all the teeth of a gear. It is the maximum out of position of any tooth with respect to any other tooth. Pitch error and runout affect the thickness, span and outside diameter are some of the important *macro-geometry* parameters of gears.

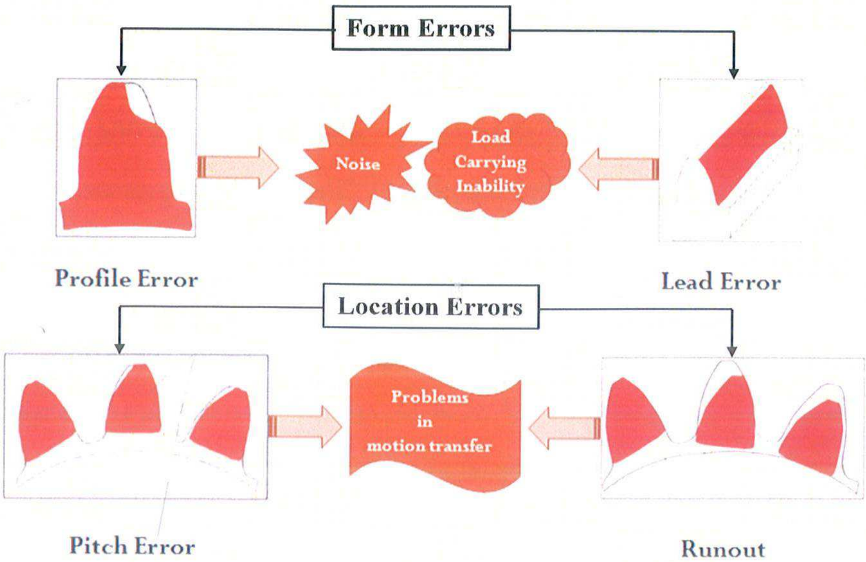


Fig. 1: Effects of errors in micro-geometry on performance of the gears.

Surface roughness refers to closely spaced surface irregularity of high frequency and short wavelength (Davim, 2010). Average roughness, maximum roughness and bearing area parameters are the important surface roughness parameters which govern the service life of a gear. Higher values of the average roughness (R_a) and maximum roughness (R_{max}) parameters can lead to early failure of the miniature gears by occurrence of wear and thereby reducing their service life. Bearing area or Abbott-Firestone curve represents the wear behaviour of a component from tribological importance point of view. Productivity of a manufacturing process helps it to sustain in a competitive environment. Generally, volumetric material removal rate (MRR) is used as a measure of the productivity of the machining processes.

WEDM has been used extensively for micro-machining and miniaturization applications because it generates quality finish, good dimensional accuracy and burr-free surfaces with excellent repeatability (Ho *et al.*, 2004; Jain, 2002; Liao *et al.*, 2004). In WEDM, the material is removed by the thermo-electric erosion process involving melting and vaporization caused by the electric spark occurring between a very thin wire and the workpiece material (McGeough, 1988). A high frequency DC pulse power is applied across the inter-electrode gap (IEG) between the wire and workpiece in the presence of a dielectric causing spark to occur which causes flow of current across the IEG. Energy contained in a tiny spark discharge removes a fraction of workpiece material. Large number of such time spaced tiny discharges between the workpiece and wire electrode cause the electro-erosion of the workpiece material. The main causes of micro-geometry errors and surface roughness in WEDMed products are irregular shaped craters produced by violent spark at high discharge energy parameter settings, adherence of wire to the workpiece surface, and deflection of wire from its intended path known as *wire lag* (Arunachalam *et al.*, 2001; Ho *et al.*, 2004; Liao *et al.*, 2004; Puri *et al.*, 2003; Williams and Rajurkar, 1991). The wire lag is caused due to impact of the electro-static forces acting on the wire, the electro-dynamic forces inherent to spark generation, the mechanical forces produced by pressure from the gas bubbles, the axial forces applied to straighten the wire and the hydraulic forces induced by the dielectric flushing.

Very limited research has been done on manufacturing of miniature gears by WEDM or EDM-based processes. Suzumori and Hori (1997) developed stator (95 teeth) and rotor (96 teeth) of steel by micro-WEDM for a prototype wobble motor used in high torque and low load applications. Takeuchi *et al.* (2000) developed a micro-planetary gear system of SKS3 tool steel and WC-Ni-Cr cermets of 0.03 mm module using micro-EDM. The manufactured gears were found good in torque transmission performance. Benavides *et al.* (2002) manufactured meso-sized ratchet wheel of different materials (e.g. 304L stainless steel, nitronic 60, austenitic stainless, beryllium copper, and titanium) by micro-WEDM with submicron level surface finish, minimum recast layer and consistent micro-geometry. Di *et al.* (2006) machined micro-gears of 40 μm module and having seven teeth with an accuracy of ± 0.2 μm from the stainless steel plate of 1 mm thickness. Ali *et al.* (2010) used WEDM to manufacture meso-sized external spur gears from beryllium-copper. The manufactured gears had seventeen teeth, outside diameter of 3.58 mm and 6 mm face width obtaining R_a, R_{max} and dimensional accuracy of 1.8 μm, 7 μm and 2-3 μm respectively for the best quality gear.

From the review of past research work, it can be concluded that no work has been reported on covering all the aspects of the WEDMed miniature gears in general and behaviour of micro-geometry parameters in particular. It also reveals the lack of work on improving the productivity and optimising the quality of WEDMed miniature gears. The present research work attempts to bridge this gap through experimental investigations, analysis, modelling, and optimization of micro-geometry, surface quality, surface integrity and productivity of the meso-sized external spur gears manufactured by WEDM. The specific objectives of the present research work were:

- To explore the capability of WEDM for manufacturing high quality miniature gears.
- To investigate and analyze the effect of WEDM parameters on micro-geometry parameters of miniature gears i.e. total profile error and accumulated pitch error.
- To investigate and analyze the effect of WEDM parameters on surface roughness parameters i.e. average roughness (R_a) value, maximum roughness (R_{max}) value and bearing area parameters.
- To investigate and analyze the effect of WEDM on surface integrity of the miniature gears by studying their microstructure and micro-hardness.
- To investigate and analyze the productivity of WEDM in terms of volumetric gear cutting rate (GCR) for manufacturing the high quality miniature gears.
- To develop the models for prediction of total profile error, accumulate pitch error, average and maximum surface roughness, and GCR using regression analysis and artificial neural networks (ANN) and their experimental validation.
- Multi-objective optimization of the WEDM parameters to simultaneously optimize the conflicting objectives of minimizing the total profile error, accumulated pitch error, average surface roughness, maximum surface roughness and maximizing the gear cutting rate (GCR).
- Comparative study of gear hobbing and WEDM to establish WEDM as a superior alternative process for manufacturing the high quality miniature gears.

The miniature external gears used in the present work had 9.8 mm outside diameter, 0.7 mm module and 12 teeth. They were manufactured on *Ecocut* WEDM machine from *Electronica* India from a 5 mm thick rectangular brass plate using brass wire of 0.25 mm diameter and de-ionized water as dielectric. Fig. 2 depicts the sequence of various tasks and the equipments used in the present work. The part programs were prepared in the *Elcam* software which has a separate segment for gear profile creation. Total profile error (F_a) and accumulated pitch error (F_p) were measured on the *SmartGEAR* CNC gear metrology machine from *Wenzel Tech Germany* using a probe of 0.5 mm diameter. The measurements were taken on the left and right flanks of four gear teeth along the functional profile for profile error and on both the flanks of all the twelve teeth at a point on the middle of the face width for the pitch error. Total profile error (F_a) was calculated by taking average of the mean values of the errors in left flank (LF) and right flank (RF) of four gear teeth. While, accumulated pitch error (F_p) was calculated by taking average of the pitch errors of RFs and LFs of all twelve gear teeth. The surface roughness parameters i.e. average roughness (R_a) and maximum roughness (R_{max}) were evaluated using *Surfcom* roughness profiler from *Accretech, Japan* on an evaluation length of 0.75 mm on gear tooth flank surface along root to tip using 0.25 mm as cut-off length. For evaluation of the volumetric *GCR*, a weight balance having resolution of 10 milligrams was used for taking the weights of the gear blank (plate of brass) before and after the gear cutting, and the gear cutting time was recorded by a stop watch having least count of 0.01 second. The following equation was used to determine the GCR value:

$$GCR = \frac{M_1 - M_2}{\rho \times t} \quad (mm^3/min)$$

where, M_1 and M_2 are the weights of the gear blank in grams before and after gear manufacturing by WEDM respectively, ρ is the density of the gear material in g/mm^3 (for brass it is 0.0084 g/mm^3), and t is the machining time in minutes.

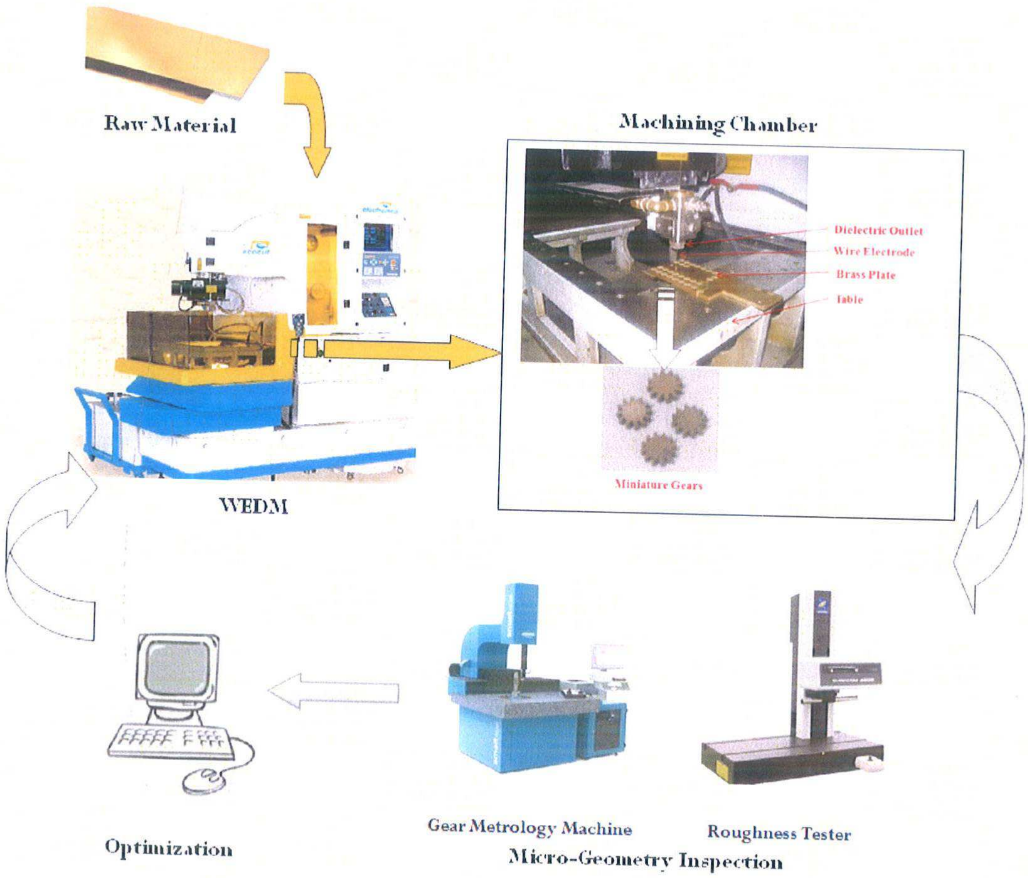
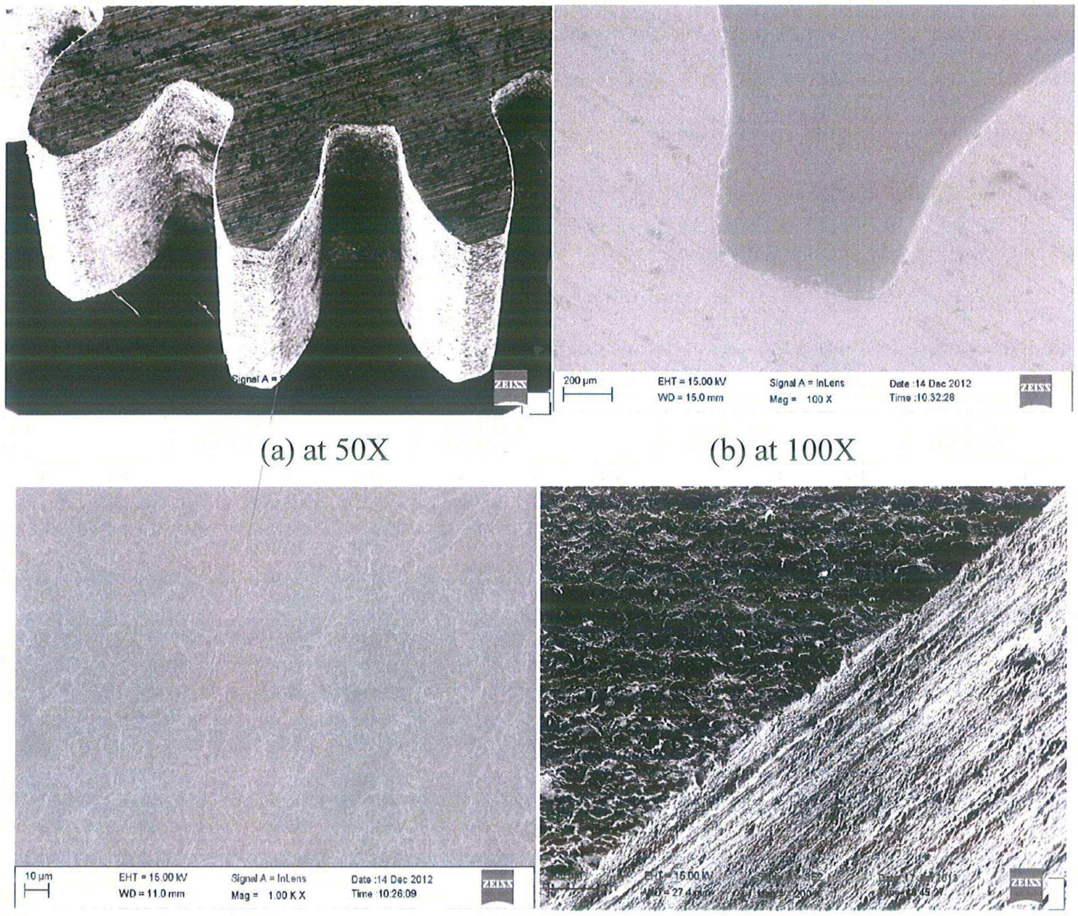


Fig. 2: Tasks and equipments used in experimental investigations on miniature gear manufacturing by WEDM.

The experimental research was accomplished in four stages, namely preliminary, pilot, main and confirmation experiments. The *preliminary experiments* were conducted to get some idea for the suitable ranges of the four most important WEDM parameters [voltage (V), pulse-on time (T_{on}), pulse-off time (T_{off}) and wire feed rate (W)] for manufacturing the brass miniature gears. These parameters were varied in their entire ranges available in the WEDM machine used and suitable ranges were bracketed with objectives to minimize wire breakage frequency and surface roughness, and to maximize machining rate. A total of twenty three *pilot experiments* were conducted using one factor-at-a-time approach by varying voltage, pulse-on time, pulse-off time and wire feed rate at five levels each and cutting speed (F) at three levels. Their objective was to further narrow down the ranges of four WEDM parameters and to fix the level of cutting speed for the main experiments on the basis of minimum errors in total profile and accumulated pitch, and minimum values of average and maximum roughness. The pilot experiments narrowed down 5-15 V for voltage; 0.6-1 μs for pulse-on time; 90-170 μs for pulse-off time; 9-15 m/min for wire feed rate and 100% for cutting speed. The best quality miniature gear manufactured at a combination of 15 V; 1 μs T_{on}; 170 μs T_{off}; 9 m/min W and at 100 % F, had *DIN* quality number 8 for profile (with total profile error of 13.2 μm) and *DIN* quality number 6 for pitch (with an accumulated pitch error of 11.2 μm). This gear had 1 μm average surface roughness and 6.4 μm maximum surface roughness with good bearing area characteristics. It was also investigated that the miniature gear had burr-free uniform tooth profile, very thin recast layer (3μm) and surface defect-free good microstructure. This gear also had very low values of macro-geometry errors i.e. deviation in span (4 μm), deviation in chordal tooth thickness (5 μm) and deviation in the outside diameter (10 μm). Fig. 3 depicts the SEM images of the this gear showing the uniform burr-free tooth profile (a-b); defect-free surface of the gear tooth (c); the arrangement of craters on tooth surface (d). Results of the pilot experiments proved that WEDM have potential and can be analyzed further for manufacturing high quality miniature gear.

The *main experiments* were designed using *Box-Behnken* approach of *response surface methodology* (RSM) by varying voltage, pulse-on time, pulse-off time and wire feed rate at three levels each. The values and levels of the parameters were chosen based on the pilot experiments, with an objective to optimize the quality of the miniature gears and productivity of the WEDM by minimizing the micro-geometry errors (i.e. total profile and accumulated pitch errors), maximizing the surface finish (by minimizing average and maximum roughness), and maximizing the volumetric gear cutting rate. A total of twenty nine experiments were conducted with two replicates for the each experiment. Therefore, total 58 gears were manufactured for main experiments.



(a) at 50X (b) at 100X

(c) at 1000X (d) at 200X

Fig. 3: SEM images, (a) and (b) burr-free and uniform gear tooth profile; (c) smooth crack-free texture of the tooth surface of the best gear; (d) craters on tooth surface of miniature gear.

'Design Expert 8.0' software was used for regression and graphical analysis of the obtained data. Analysis of variance (ANOVA) found that all four WEDM parameters significantly affect all the responses. The RSM based regression models were developed to establish the relationship between WEDM parameters and the responses. Minimum values of F_a and F_p were obtained in the range of 8-9 volts voltage, 150-170 μs pulse-off time and 12-15 m/min wire feed rate and at lower pulse-on time, because of the minimum wire lag, lower frequency of wire breakage and lower discharge energy in these ranges. For R_a to be minimum, the machining should be at lowest voltage, shortest pulse-on time, highest pulse-off time and maximum wire feed rate whereas, for minimum R_{max} the optimum ranges of voltage (6-8 V), pulse-on time (0.6-0.7 μs) and wire feed rate (12-15 m/min) exist. Experimental results also reveal that, high gear cutting rate (GCR) can be achieved by higher voltage, longer pulse-on time, shorter

pulse-off time and wire feed rate in the range of 13-14 m/min. The WEDM parameters were further optimized to get minimum values of F_a, F_p, R_a, R_{max} and maximum value of *GCR* using *desirability analysis.* ANN models were also developed establishing the relation between WEDM parameters and responses for further predictions. It was found that the predictions of the ANN models are better than RSM based models. The multi-objective optimization was done for simultaneous minimization of (a) F_a and F_p, (b) R_a and R_{max} by desirability analysis and (c) minimization of F_a, F_p, R_a, R_{max} along with maximization of GCR using desirability analysis and integrated ANN-GA (genetic algorithm) approach. Finally, the confirmation experiments were conducted, and the results of single and multi-objective optimizations were validated.

Some Significant Findings and Conclusions

- The miniature gears manufactured by WEDM have DIN quality number 5 and 7 for pitch and profile respectively which are much superior than the quality of the gears manufactured by other conventional processes.
- The average roughness and maximum roughness for the optimized gear is up-to 1.05 μm and 6.34 μm respectively which are acceptable for micro-machining and miniaturization applications.
- The WEDMed miniature gears retain good tribological properties and long service life as they posses uniform tooth profile, defect-free tooth surface with good microstructure.
- The findings of the present work prove the capability of WEDM process for manufacturing high quality miniature gears.
- The comparison of WEDMed and hobbed gear proves the superiority of WEDM process.

The experimental investigations of the present work explore and establish WEDM as a superior alternative process for manufacturing of high quality miniature gears used in precise miniaturised devices. Scope for future work may include (i) investigating the effects of other WEDM parameters such as wire tension, flushing pressure and discharge current on the quality of WEDMed miniature gears, and (ii) investigations on the quality of WEDMed miniature gears made of other gear materials such as stainless steel, bronze and aluminium.