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AN INVESTIGATION ON MEAN ROUGHNESS DEPTH AND MATERIAL EROSION SPEED DURING MANUFACTURING OF STAINLESS-STEEL MINIATURE RATCHET GEARS BY WIRE-EDM

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Abstract. *This paper presents the results of an investigation conducted on wire electric discharge machining (wire-EDM) of miniature ratchet gears. Effects of three important process parameters spark duration, 'T_{on}', spark-off-duration 'T_{off}', and wire tension 'WT' on surface quality, i.e., mean roughness depth 'R_z' and productivity, i.e., material erosion speed 'MES', have been investigated by conducting seventeen experimental trials. Both T_{on} and T_{off} have been identified as the significant parameters. Further, an optimization of wire-EDM parameters resulted in simultaneously best compromise values of R_z 5.30 µm and MES 6.75 mm/min and is achieved the following cutting regime: T_{on} 1.5 µs, T_{off} 42.5 µs, and W_T 1500 g. At the end, surface quality study has been conducted to evaluate the tribological fitness of the miniature ratchet gear machined at optimum combination of wire-EDM parameter values. It was investigated that the generation of uniform and shallow craters on the flank surfaces of ratchet gear machined at optimum values of parameters, imparted smoother bearing area curve and lower coefficient of friction. The profile and flank surface of the ratchet gear also found free from cracks, burrs, and dirt.*

Key words: *Optimization, Ratchet Gear, Surface Roughness, Tribology, Wire-EDM*

1. INTRODUCTION

A wheel having uniform but asymmetrical teeth at identical spaces on its circumference is widely referred to as a ratchet wheel/gear [1]. Each tooth of ratchet gear has a gentle slope on one edge and a steep slope on the other edge. It receives an intermissive annular motion from an oscillating or reciprocating member. But it doesn't transfer motion and

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power from one shaft to another shaft like a gear. A ratchet gear is a key element of mechanical devices which permits one directional rotary or linear motion during its rotation in the forward direction and fending any movement in the reverse direction. Ratchet gears are widely used in power wrench, ratchet spanners, lifting devices (hoist), watches, turnstiles, ratchet winder, watch winders; cable tie, fishing reel, overrunning clutch, etc. [1, 2].

Surface roughness parameters define the micro irregularities on flank surfaces of the ratchet gears. These irregularities are the indication of variation of the actual surface profile (i.e. top machined surface) from the nominal surface or means line of the surface profile [3]. In practice, surface roughness is considered as one of the most important criteria for assessing the quality of machined surfaces [4, 5]. Friction and wear are two most important tribology parameters for sliding or rolling parts and largely depend on the quality of the manufactured surface. A rough surface, high coefficient of friction, crack, inclusions, burrs etc. adversely affect the tribological fitness of the mechanical components like gears [3, 6]. A compromise with the tribological fitness may lead to high consumption of energy and resources, and failure of the mechanical parts and components [7].

Therefore, it becomes necessary to minimize the surface roughness for better tribological fitness of manufactured parts and components. Since post finishing processes are aimed to remove surface irregularities, but are time consuming and lead to extra cost and environmental footprints, the attempt should be to generate the most favorable surface characteristics using the manufacturing process itself. The conventional processes namely extrusion, forging, die-casting, and powder particle processing, are commonly used to manufacture miniature ratchet gears from a variety of materials [8, 9]. But, these processes have some restrictions related to material selection and part, i.e., gear thickness, occurrence of tool marks, generation of a poor surface quality, etc. These limitations compel to explore alternate processes to manufacture miniature ratchet gears.

In the past decade, wire electrical discharge machining (wire-EDM) has drawn an attention of manufacturers worldwide due to its potential to machine difficult-to-machine materials, miniature products, machine precisely, and to run without interruption for a long period of time for big jobs [10]. This process is based upon the principle of thermoelectric erosion where the material removal takes place by erosion due to the occurrence of sparks between two electrodes as a thin wire (cathode) and workpiece (anode) and supplying a suitable dielectric between them. There has been some past attempts to use this technology for machining gears from a wide range of engineering materials. But, no record is found on machining a ratchet wheel using this process. Some of the important past works are discussed here as under.

Wang et al. [11] fabricated ten micro spur gears (0.1 module) from X153CrMoV12 material by micro wire-EDM and achieved 0.9 µm as the average roughness of manufactured micro gears. Chaudhary et al. [12] investigated the influence of peak current, spark duration, spark-off duration, wire tension, and dielectric fluids on the maximum roughness depth of miniature gears (∅7mm) fabricated by wire-EDM. Mohapatra et al. [13] fabricated macro spur gears having a 20 mm pitch circle diameter from the copper plate by Wire-EDM and found 1.78 µm as the average roughness of macro gears. Chaubey and Jain [14] studied the influence of wire-EDM parameters on surface quality of stainless steel helical and bevel gears. They successfully fabricated high manufacturing quality gears. Benavides et al. [15] manufactured better surface quality miniature ratchet gears from four different materials by micro wire-EDM process using ø30 µm tungsten wire. Ali and Mohammad

[16] achieved 1 µm average roughness and 7 µm maximum roughness depth of miniature gears by wire-EDM at lower values of spark duration, voltage, and discharge current.

The above review of relevant past work shows the potential of wire-EDM for manufacturing miniature gears. But, after a literature review, it is identified that a detailed investigation on wire-EDM of ratchet gear, is yet to be explored.

With an aim to fill this gap, the present work investigates the wire-EDM manufacturing of miniature ratchet wheel and its parameters' effects on surface quality of the gears and productivity of the process. Given that surface quality and process productivity are in general opposite process performances, a multi-objective optimization problem was formulated and solved in order to identify the set of process parameter values that enable achievement of best trade-off.

2. Experimentation and Measurements

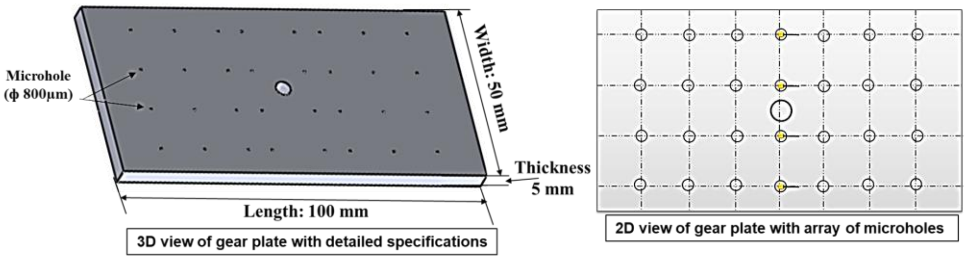
2.1. Materials and machine

Asymmetric miniature ratchet gears that have 8 teeth were manufactured from a 5 mm thick rectangular plate made of austenitic stainless steel of grade 304 (SS304). The specifications and material description of the ratchet gear are given in Table 1.

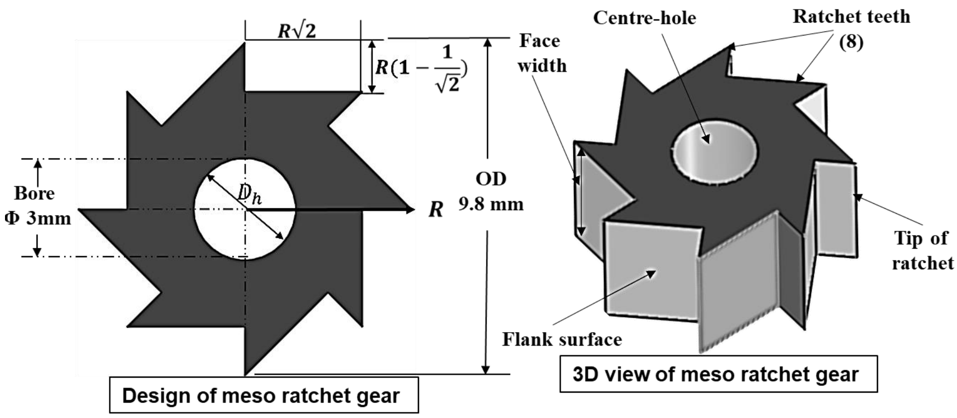
Table 1 Specifications of miniature ratchet gear and composition of gear material

Miniature ratchet gear specifications
Material: SS 304; Profile: asymmetric, Addendum diameter: 9.8 mm; No. of teeth: 8; Face width: 5 mm; Center-hole diameter: 3 mm
Composition (% wt.) of ratchet gear material (SS 304)
0.8% C; 6.8% Ni; 17% Cr; 1.2% Mn; 1% Si; 0.5% S; Balance Fe

Figure 1 presents two and three-dimensional views of a rectangular plate and miniature ratchet gear with detailed specifications. Miniature ratchet gears were fabricated by a non-submerged type vertically traveling Wire-EDM machine (Model: Sprintcut win; Brand: Electronica; Country of origin: India) as shown in Fig. 2. A very fine soft zinc-coated brass wire of 0.25 mm diameter having 800 N/mm^2 tensile strength was used as tool electrode for cutting of miniature ratchet gears from SS 304 rectangular plate in the presence of deionized water acts as a dielectric medium. The wire-EDM machine used for fabricating miniature ratchet gears has computer numerical controlled (CNC) 4 axis (X, Y, U, and V) with the capability to achieve wire inclination angle up to ± 30^0. The complex and tapered parts (i.e., gears) having dissimilar top and bottom faces can be fabricated by wire-EDM using the inclination angle of wire. Wire tension/rigidity is maintained between the upper and lower guide to ensure smooth machining by avoiding wire vibrations. ELCAM software was used to make a part program for ratchet gear cutting.



(a)



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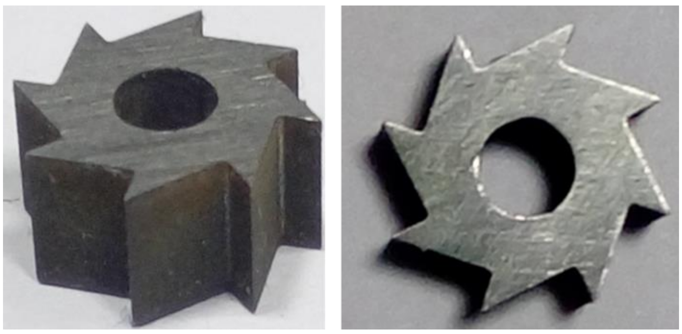


(c)

Fig. 1 2D and 3D views of (a) gear blank in form of rectangular plate; and (b) miniature ratchet gear drawing; (c) actual pictures of ratchet gears fabricated from SS 304 plate by wire-EDM

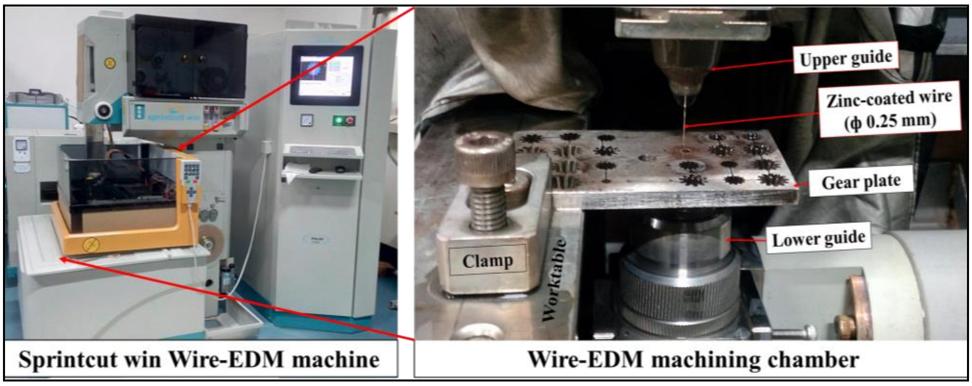


Fig. 2 Wire-EDM machine tool used for this study and enlarged view of machining chamber during cutting of miniature ratchet gear

2.2. Experiment procedure and measurements

To study the effect of three variable wire-EDM parameters, a total of seventeen experimental trials were planned and conducted according to the Box–Behnken experimental design. Box-Behnken is a rotatable design and requires only three levels of variation for each parameter [17], whereby parameter combinations do not coincide with factorial or fractional designs and are located at the midpoints of parameter's ranges including several central points. This property makes this design useful in situations when one needs to avoid potential loss of experimental data which could result because of performing experimental trials in which all parameters have extreme values. Each experimental trial was replicated twice in order to reduce the effect of uncontrolled variation and improve statistical accuracy of the experiment. Thus, in total, thirty-four miniature ratchet gears were manufactured by wire-EDM. Table 2 presents the values of the constant parameters, variable parameters, and their coded levels and corresponding values of the variable parameters of wire-EDM. These parameters, their values and levels were selected based on literature review, some preliminary experiments, and considering machine constraints.

In this study, material erosion speed *(MES)* and surface roughness parameter, i.e., mean roughness depth (R_z), were considered as responses to study the surface quality of gears and productivity of the process. In wire-EDM, material erosion speed indicates the movement of wire (in mm) per unit time (in second) according to the path of prepared gear part-program, during cutting of ratchet gears. It also indicates the productivity of wire-EDM in mm/min and can be calculated by dividing the total path length (TPL_{RG}) travelled by wire by the total time (TCT_{RG}) taken for cutting miniature ratchet gear. Following the geometry of miniature ratchet gear, the total path length was 71.82 mm and the total machining time was recorded from the display unit of the wire-EDM machine during cutting of every ratchet gear. The following equation was used to calculate the material erosion speed.

$$MES = \frac{TPL_{RG} \text{ for cutting ratchet gear with centerhole}}{TCT_{RG} \text{ for cutting ratchet gear with centerhole}} \left(\frac{mm}{\min} \right) \qquad (1)$$

Table 2 Details of the selected wire-EDM input parameters [18]

Variable wire-EDM process parameter				Considered responses
Name, 'symbol' and (unit)	Actual (coded) levels			
	Low (-1)	Medium (0)	High (1)	
Spark duration 'T_{on}' (μs)	0. 9 (-1)	1.3 (0)	1.7 (1)	Material erosion speed (*MES*)
Spark-off duration 'T_{off}' (μs)	40.5 (-1)	44.5 (0)	48.5 (1)	Mean roughness depth (R_z)
Wire tension 'W_T' (g)	780 (-1)	1140 (0)	1500 (1)	
Constant parameters				
Wire-EDM parameters: Peak current 'I_P': 12 A; Servo voltage 'S_V': 20 Volts; Flushing pressure 'W_P': 15 kg/cm^2; Cutting speed 'C_S': 100 %				
Workpiece and wire: Electrode material: Zinc coated wire; Wire diameter: 0.25 mm; Wire tensile strength: 800 N/mm^2; and Gear materials and thickness: SS 304 and 5 mm				
Dielectric: Deionized water; Dielectric conductivity: 20 mho				

The mean roughness depth 'R_z' was considered as the surface roughness parameter to evaluate the flank surface quality of the miniature ratchet gears fabricated by the wire-EDM process. LD 130 3D-surface roughness cum contour tracing machine from Mahr metrology (Germany) was used for the measurements of the mean roughness depth 'R_z'. This instrument was also used to check bearing area curve (BAC). To test tribological fitness for the machined ratchet gear, a linear reciprocating wear testing machine (Model: CM9104 from Ducom, USA) was used under dry conditions at room temperature by sliding a 6 mm diameter tungsten carbide ball (950 HV 9 hardness) for a 5 mm distance at 15 Hz frequency for 15 minutes time duration under 15N normal load on a single tooth of gear sample. Scanning electron microscope (SEM) SUPRA 55 from Carl Zeiss (Germany) was used for analysis of flank surfaces of the best quality gear.

3. Results and Discussion

Table 3 presents the combination of wire-EDM parameters and their corresponding values of responses obtained after conducting the experiment. The average values of the responses obtained in replicates ($Repl_1$+$Repl_2$) are considered.

Empirical models usually require the use of statistical tests for the assessment of significant model terms [19]. In this study analysis of variance (ANOVA) was used for the analysis (Tables 4 and 5). The following interpretations are drawn from the ANOVA:

- The significance of developed models for each response was identified by using a 95% confidence interval of P-values (i.e., p-values must be less than 0.05).
- The developed quadratic models are significant since their P-value is less than 0.05.
- Only T_{on} and T_{off} were found statistically significant for both responses. Also, in the models for predicting mean roughness depth and material erosion speed, interaction of spark duration and wire tension ($T_{on}W_T$) and quadratic effect of the spark duration were close to statistical significance.
- A non-significant lack of fit, as desirable, is obtained indicating that developed models accurately fit experimental data.

Table 3 Experimental trials and obtained results for fabrication of ratchet gears by wire-EDM

Exp. trials	Wire-EDM process parameters			Mean roughness depth 'R_z'(μm)	Material erosion speed 'MES' (mm/min)	Machining time (min)
	Spark duration 'T_{on}' (μs)	Spark-off duration 'T_{off}' (μs)	Wire tension 'W_T' (g)	Avg. (Repl$_1$ +Repl$_2$)	Avg. (Repl$_1$ + Repl$_2$)	Avg. (Repl$_1$ + Repl$_2$)
1	0.9 (-1)	40.5 (-1)	1140 (0)	5.93	4.94	14.68
2	*1.3 (0)*	*44.5 (0)*	*1140 (0)*	4.76	5.28	13.60
3	1.3 (0)	48.5 (1)	780 (-1)	4.18	4.98	14.42
4	0.9 (-1)	44.5 (0)	1500 (1)	5.19	3.65	22.93
5	1.7 (1)	44.5 (0)	780 (-1)	9.34	6.1	11.40
6	*1.3 (0)*	*44.5 (0)*	*1140 (0)*	6.38	6.1	12.17
7	1.3 (0)	40.5 (-1)	1500 (1)	8.07	7.98	10.60
8	1.3 (0)	44.5 (0)	1140 (0)	4.8	6.53	10.67
9	1.3 (0)	40.5 (-1)	780 (-1)	9.25	7.08	10.75
10	0.9 (-1)	48.5 (1)	1140 (0)	4.19	3.61	19.87
11	*1.3 (0)*	*44.5 (0)*	*1140 (0)*	4.95	5.63	12.75
12	1.7 (1)	40.5 (-1)	1140 (0)	9.65	7.57	9.75
13	1.7 (1)	44.5 (0)	1500 (1)	5.22	6.46	9.95
14	1.3 (0)	48.5 (1)	1500 (1)	3.74	4.33	14.72
15	*1.3 (0)*	*44.5 (0)*	*1140 (0)*	6.78	4.95	12.57
16	0.9 (-1)	44.5 (0)	780 (-1)	3.69	4.06	17.67
17	1.7 (1)	48.5 (1)	1140 (0)	8.67	5.73	12.53

- The values of coefficient of determination (R^2) are 0.8518 and 0.9096 for mean roughness depth and material erosion speed which are close to 1. Therefore, these values also confirm the adequacy of the developed response models indicating that the developed models are able to explain significant portions of the variability of the responses.
- The values of adequate precision greater than 4 are desirable for the developed response models. It indicates the signal-to-noise ratio, i.e., compares the range of the predictions in experimental trials to the average prediction error. The values of adequate precision are 7.458 and 10.231. Therefore, it can be confirmed that developed response models indicate adequate signals.
- The developed response surface models for mean roughness depth 'R_z', and material erosion speed '*MES*' can be expressed through the following empirical equations in terms of coded values of process parameters:

$$R_z = 5.53 + 1.73T_{on} - 1.52T_{off} - 0.53W_T + 0.56T_{on}^2 + 1.01T_{off}^2 - 0.24W_f^2 + 0.19T_{on}T_{off} - 1.4T_{on}W_T + 0.18T_{off}W_T \quad (2)$$

$$MES = 5.7 + 1.20T_{on} - 1.12T_{off} + 0.033W_T - 0.63T_{on}^2 + 0.39T_{off}^2 - 0.25W_f^2 - 0.12T_{on}T_{off} + 0.19T_{on}W_T - 0.39T_{off}W_T \quad (3)$$

Table 4 Results of ANOVA for mean roughness depth measured during experiments on Wire-EDM of ratchet gear

Source	Sum of squares	DF	Mean square	F-value	P-value	Remarks
Model	58.89	9	6.54	4.47	0.0305	Significant
T_{on}	24.08	1	24.08	16.46	0.0048	Significant
T_{off}	18.36	1	18.36	12.55	0.0094	Significant
W_T	2.25	1	2.25	1.54	0.2552	Not significant
T_{on} T_{off}	0.14	1	0.14	0.099	0.7626	Not significant
T_{on} W_T	7.90	1	7.90	5.40	0.0532	Not Significant
$T_{off}W_T$	0.14	1	0.14	0.094	0.7686	Not significant
(T_{on}^2)	1.33	1	1.33	0.91	0.3714	Not Significant
(T_{off}^2)	4.32	1	4.32	2.95	0.1294	Not significant
(W_T^2)	0.24	1	0.24	0.16	0.6997	Not significant
Residual	10.24	7	1.46			
Lack of fit	6.50	3	2.17	2.31	0.2178	Not significant
Pure error	3.75	4	0.94			
Cor Total	69.13	16				
R-Squared = 0.8518, Adjusted R-Squared = 0.6613, Adequate Precision = 7.458						

Table 5 Results of ANOVA for material erosion speed measured during experiments on Wire-EDM of ratchet gear

Source	Sum of squares	DF	Mean square	F-value	P-value	Remarks
Model	24.51	9	2.72	7.82	0.0064	Significant
T_{on}	11.52	1	11.52	33.09	0.0007	Significant
T_{off}	9.95	1	9.95	28.57	0.0011	Significant
W_T	5.000E-003	1	5.000E-003	0.014	0.9080	Not Significant
$T_{on}T_{off}$	0.065	1	0.065	0.19	0.6786	Not Significant
T_{on} W_T	0.15	1	0.15	0.43	0.5349	Not Significant
$T_{off}W_T$	0.60	1	0.60	1.73	0.2305	Not significant
(T_{on}^2)	1.67	1	1.67	4.80	0.0645	Not significant
(T_{off}^2)	0.66	1	0.66	1.88	0.2122	Not significant
(W_T^2)	2.632E-007	1	2.632E-007	7.558E-007	0.9993	Not significant
Residual	2.44	7	0.35			
Lack of fit	0.84	3	0.28	0.71	0.5961	Not significant
Pure error	1.59	4	0.40			
Cor Total	26.95	16				
R-Squared = 0.9096, Adjusted R-Squared = 0.7933, Adequate Precision = 10.231						

3.1. Influence of wire-EDM parameters

In this section, the influence of considered input parameters of wire-EDM, namely, spark duration 'T_{on}', spark-off duration 'T_{off}', and wire tension 'W_T' on the considered responses (i.e., mean roughness depth 'R_z' and material erosion speed '*MES*') is discussed with the help of graphs, as shown in Figs. 3a and 3c. In these graphs, the abscissa depicts the values of roughness parameters in µm and material erosion speed in mm/min, whereas, the ordinate shows the values of variable input parameters of wire-EDM. Figures 3a and 3c depict the influence of spark duration, spark-off duration, and wire tension on the selected responses, respectively. The prominent inferences drawn from Figs. 3a and 3c are as follows:

- Mean roughness depth 'R_z' and material erosion speed '*MES*' are continuously increasing with an increase in spark duration. Their minimum and maximum values occur at 0.9µs and 1.7µs of spark duration.
- Mean roughness depth 'R_z' and material erosion speed '*MES*' are continuously decreasing with an increase in spark-off duration. The minimum values of roughness parameters and maximum values of material erosion speed occur at 48.5 µs and 40.5µs of spark-off duration, respectively.
- Wire tension has no significant influence on the mean roughness depth 'R_z' and material erosion speed '*MES*'. Though, it was observed that mean roughness depth 'R_z' very slightly decreases with an increase in wire tension. Whereas, material erosion speed slightly increases (ranging from 5.56 to 5.61 mm/min) with wire tension.

Spark duration is the time period of occurrence of sparks in the machining zone between wire electrode and workpiece material being machined [14, 16]. At higher values of spark duration, spark occurs for a longer period of time and consequently material removal is more due to high material erosion speed. Further increase in the spark duration leads to the generation of rough surface on the workpiece by the formation of non-uniform craters and hence the surface roughness is high. Spark-off duration is the time period when no spark occurs and no machining takes place. For a duty cycle having a low spark-off duration, means high frequency of spark occurrence. Increase in spark-off duration leads to decrease in spark duration and material erosion speed is low for that duty cycle. Uniform and shallow craters occur on the surface being machined, for such duty cycle and surface roughness decreased. Wire tension is the straightness of the wire between the upper and lower guides of the wire-EDM machine tool. In case of low values of wire tension, its straightness is low and due to which vibrations are high. In such case, flushing of the debris, i.e., machined material from the wire-workpiece gap, is poor which deteriorates the surface quality of the workpiece and results in rough surface. Moreover, due to inefficient flushing the material erosion speed is also very low at low wire tension. The higher wire tension ensures the smooth flushing of debris from inter-electrode gaps thus ensuring the better surface quality as well as productivity of wire-EDM.

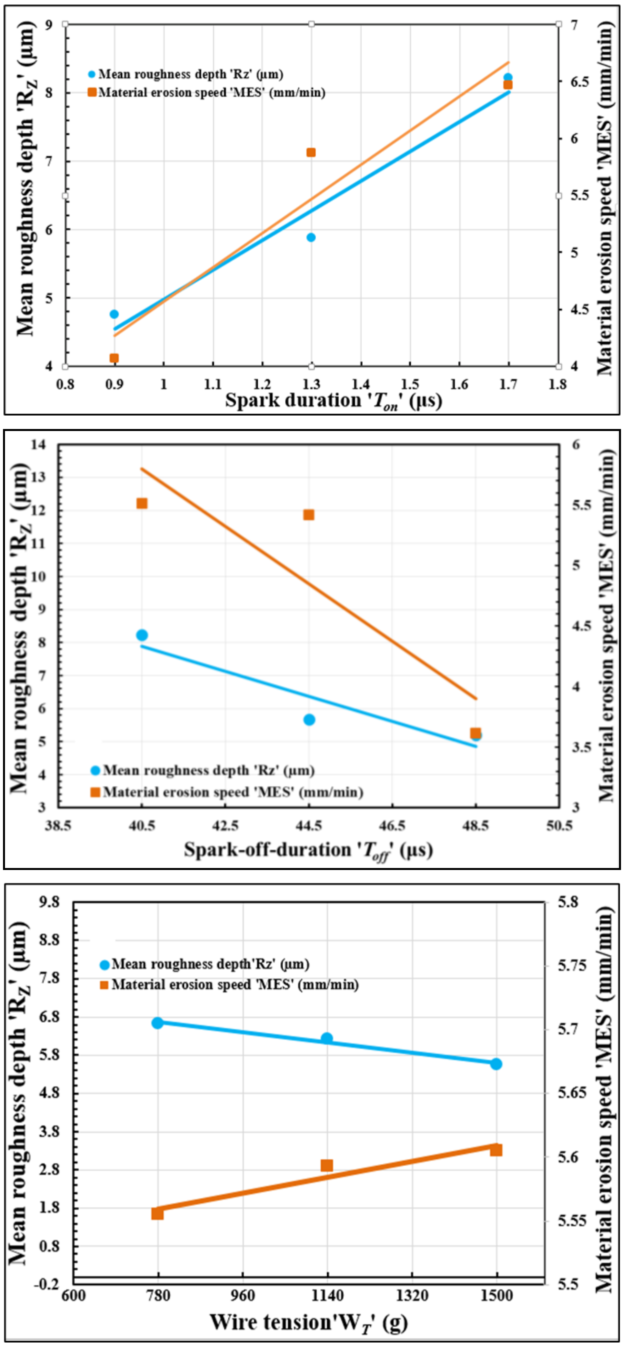
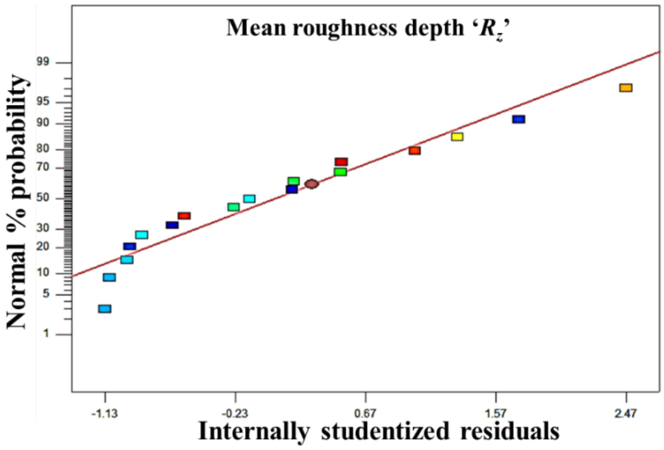
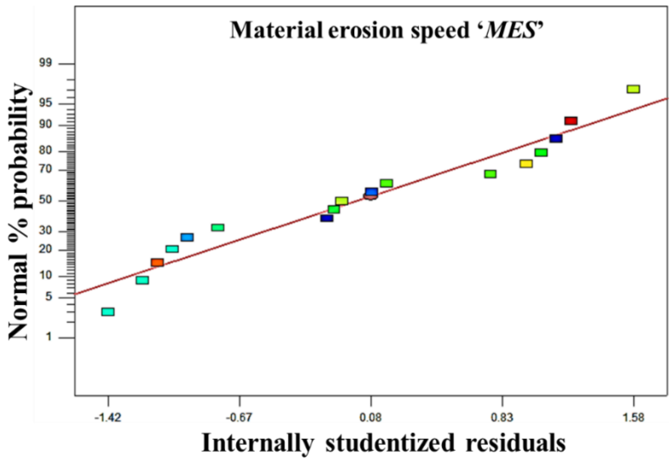


Fig. 3 Effect of wire-EDM parameters on mean roughness depth and material erosion speed during manufacturing of ratchet gear: a) Effect of spark duration; b) Effect of spark-off duration; c) Effect of wire tension

Figures 4a and 4b present the normal probability graphs for mean roughness depth (R_z) and material erosion speed (*MES*). These graphs show the distribution of residuals along a straight line referred to as the mean line and are helpful for residual analysis. It can be observed from Figs. 4a and 4b that all seventeen residuals for the seventeen experimental data sets are located within a close proximity of the mean line, that confirms the normal distribution of the residuals for mean roughness depth and material erosion speed. In other words, it is evident from the normal probability distribution residual graphs that results data sets for mean roughness depth and material erosion speed, for all experimental runs are not much scattered with a high probability of following the same pattern, and statistically fit for establishing a relationship with the wire-EDM process parameters for future predictions.



a)



b)

Fig. 4 Normal probability distribution graphs of residuals for selected responses: (a) mean roughness depth 'R_z' and (b) material erosion speed '*MES*'

3.2. Multi-objective optimization and experimental validation

Desirability function analysis (DFA) is a widely used technique for the simultaneous optimization of multiple responses to obtain the optimal set of parameters [20-22]. The idea of DFA is to transform the multi-objective into single-objective problem, by estimating overall desirability function (composite desirability) [23]. Depending upon the type of the objective function, the following two equations were used to compute the desirability of each response for the i^{th} experimental observation and using a target value equal to a minimum value of roughness response and maximum value of material erosion speed response identified from its experimental values.

For minimization of the mean roughness depth (i.e., smaller-the-better type):

$$u_i = \left(\frac{A - y_i}{A - S} \right)^{w_i} \tag{4}$$

For maximization of the material erosion speed (i.e., larger-the-better type):

$$u_i = \left(\frac{y_i - B}{S - B} \right)^{w_i} \tag{5}$$

$$U = (u_1, u_2, ..., u_n)^{\frac{1}{n}} = \left(\prod_{i=1}^{n} u_i \right)^{\frac{1}{\sum w_i}} \tag{6}$$

where u_i is the desirability of all responses y_i and U is the combined desirability function, S is the objective value, A is the permissible upper value of the i^{th} response, B is the permissible lower value of the i^{th} response, w_i is the relative importance or weightage assigned to the response y_i, and n is the total number of responses.

A combined desirability value closer to 1 is selected to have an optimum combination. The following equations are used to compute the desirability for the i^{th} combination of considered responses by assigning equal weightage (0.5).

For minimization of the mean roughness depth (i.e., smaller-the-better type):

$$u_{R_{zi}} = \left(\frac{R_{z\max} - R_{zi}}{R_{z\max} - R_{z\min}} \right)^{0.5} \tag{7}$$

For maximization of the material erosion speed (i.e., larger-the-better type):

$$u_{MES_i} = \left(\frac{MES_i - MES_{\min}}{MES_{\max} - MES_{\min}} \right)^{0.5} \tag{8}$$

where R_{zmax}, MES_{max}, R_{zmin}, and MES_{min} are the maximum and minimum values of mean roughness depth and material erosion speed. The maximum values used for mean roughness depth and material erosion speed are 9.65 µm and 7.98 mm/min, respectively. While corresponding minimum values are 3.69 µm and 3.61 mm/min, respectively.

The overall desirability function, U_i, for the i^{th} combination of the selected parameters of wire-EDM can be computed using Eqs. (9) and (10):

$$U_i = \left[\{(u_{R_z})_i\}\{(u_{MES})_i\}^{0.5} \right]^{\frac{1}{0.5+0.5}} \tag{9}$$

$$U_i = \left[\{(u_{R_z})_i\}\{(u_{MES})_i\}^{0.5} \right] \tag{10}$$

The desirability predicted optimum values of wire-EDM parameters are not exactly what can be set of wire-EDM machine tool. Therefore, the adjacent standard values of input parameters available in the wire-EDM machine corresponding to their optimized values were selected for conducting the two confirmation experimental trials to validate the optimized results obtained from DFA. The average values of considered responses obtained from confirmation experimental trials were used to calculate the difference between confirmation results and optimum results obtained from DFA (Table 6).

Table 6 Results of optimization in terms of desirability predictions and experimental validation

Wire-EDM parameter		Optimized value by DFA	Experimental validation (i.e., close standard values available in the wire-EDM)		Avg. value	Error
			Trial$_1$	Trial$_2$		
Wire-EDM process parameters	T_{on} (μs)	1.51	1.5			
	T_{off} (μs)	42.77	42.5			
	W_T (g)	1500	1500			
Responses	R_z (μm)	5.86	5.25	5.35	5.30	9.6%
	MES (*mm/min*)	7.06	6.72	6.77	6.75	4.4%

Table 6 presents optimum values of machining combination and responses obtained for the best desirability function value of 0.842. It also presents the actual values obtained after validation experimental trials. The average (of trials 1 and 2) values of mean roughness depth and material erosion speed are 5.30 µm and 6.75 mm/min, respectively. The percentage difference between confirmation results and optimum results obtained from desirability prediction is less than 10% and can be considered as the worthy agreement between predicted and actual values.

3.3. Surface quality study

Figures 5a and 5b depict the 2D surface roughness profiles and 3D surface topographies for the best quality ratchet gear R_z- 5.30 µm machined at optimum valued of wire-EDM parameters and the ratchet gear R_z- 9.65 µm machined using wire-EDM parameter values as given in experimental trial 12, respectively.

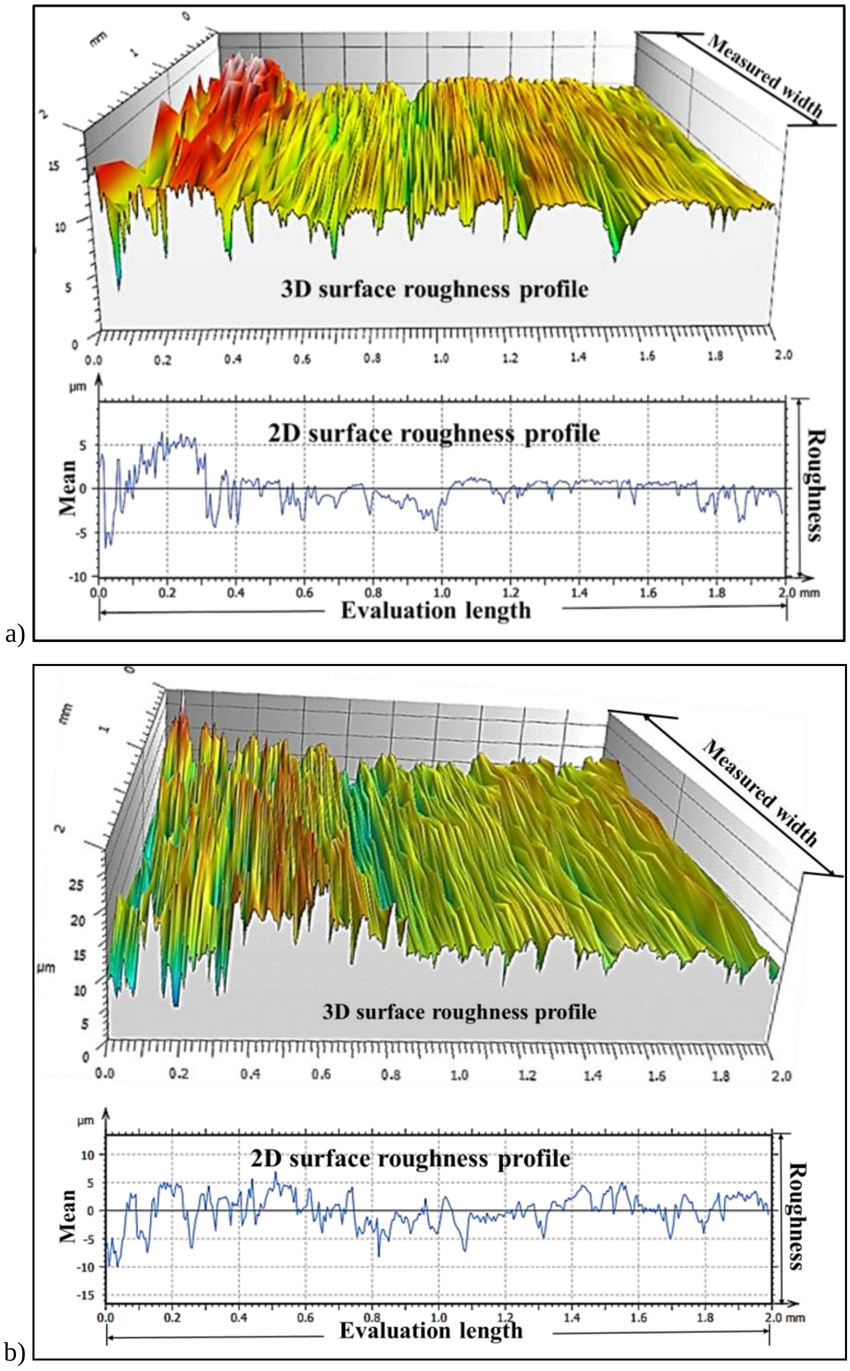


Fig. 5 2D profiles and 3D topographies for surface roughness of (a) best quality ratchet gear, (b) poor quality ratchet gear

The deteriorated surface quality is evident for the ratchet gear having higher roughness and machined at experimental trial 12. The Abbott-Firestone curve referred to as the bearing area curve (BAC) and describes the surface texture of manufactured parts and components [24, 25]. As shown in Fig. 6a, BAC represents as a graph plotted between maximum roughness and the percentage evaluation length. This graph is useful to identify the real contact area of mating surfaces and the change in that contact area, as a result of the wear of manufactured parts and components (e.g., Rpk). Rpk portion disappears in the running-in operation (function) of the part surface. It is also useful to determine lubricant retention for manufactured parts and components (e.g., Rvk). Rvk portion does not participate in any task or function during operation and serves to anchor the lubricating film. Rk indicates the depth of core roughness profile area and determines the intended service life of parts. It is the actual area which comes in contact with other parts during rolling or sliding [25].

Figures 6, 7 and 8 depict bearing area curves of the theoretical concept, best surface quality miniature ratchet gear R_z- 5.30 µm and poor surface quality miniature ratchet gear R_z- 9.65 µm (corresponding to experimental trial 12 in Table 2), respectively. The BAC of the best surface quality gear is smoother and bearing area ratio is higher as compared to the poor surface quality gear. It is due to the formation of uniform and shallow craters that tend to lesser irregularities on the flank surfaces of the best quality ratchet gear. It is evident from Figs. 7 and 8 that the best quality ratchet gear has less material available to worn out during preliminary contact and a better lubrication capacity than poor-quality ratchet gear. The material portion 'Mr2-Mr1' (the percentage of material available during actual contact) of the best quality ratchet gear within the corresponding region is 74.98 % which is higher than the material portion 68.0% of the poor-quality gear. Percentage bearing length (B_L) (the total material available during tribological interaction) of the best quality ratchet gear (81%) is also higher than the poor quality gear (78.6%). These results confirm that the ratchet gear machined at optimal wire-EDM parameters has the best surface quality that leads to its tribological fitness.

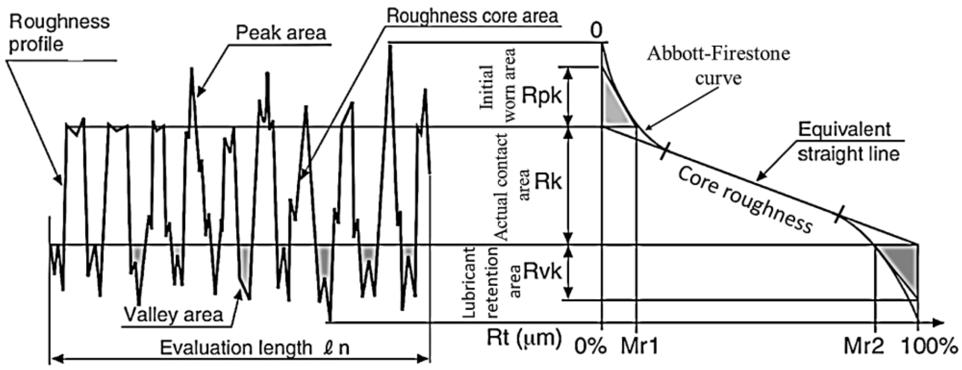


Fig. 6 Theoretical concept of bearing area curve

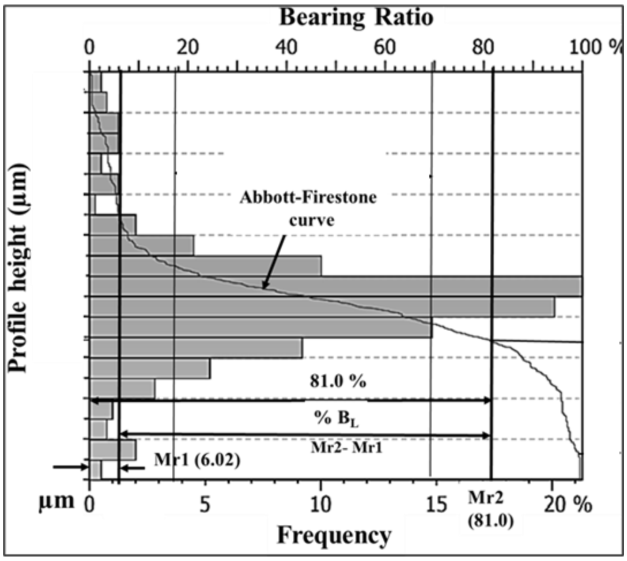


Fig. 7 Bearing area curve for the best surface quality ratchet gear

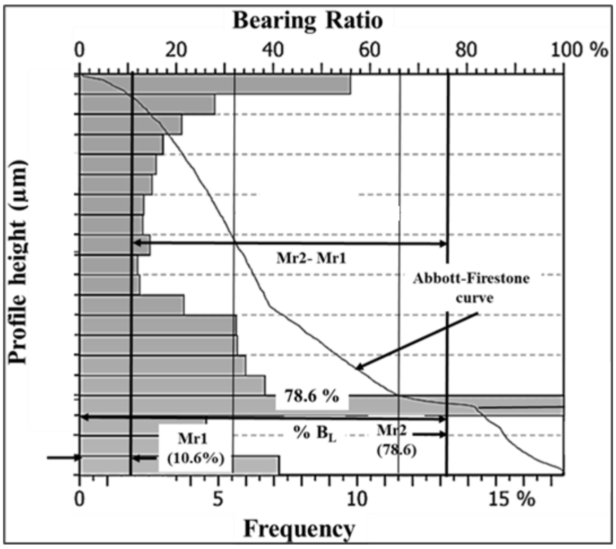
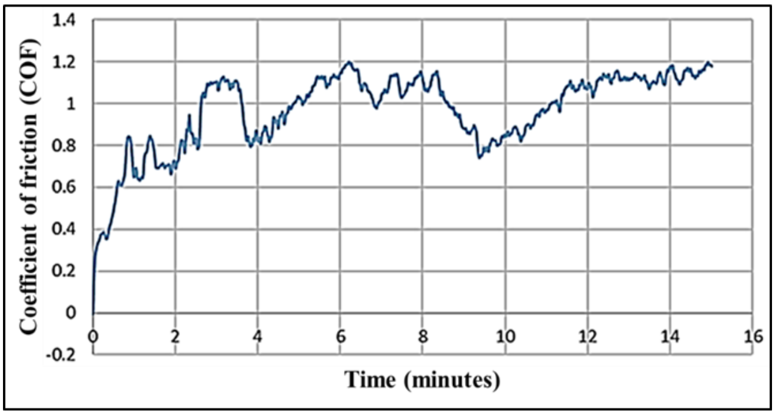


Fig. 8 Bearing area curve for poor surface quality ratchet gear

The coefficient of friction (COF) which is a ratio between friction and normal forces depends on adhesion and roughness between two surfaces. Although some amount of COF is a must, but for most of the applications, a low value of COF is desirable [26, 27].

Figures 9a and 9b depict the COF curves for poor surface quality miniature ratchet gear and optimum miniature ratchet gear. These curves illustrate the variation of COF with fretting wear time in minutes. It can be seen from Fig. 9a that COF increases initially and goes beyond 1. Further, it becomes constant for a small duration and is then decreases for 4 minutes of wear. It starts increasing again up to 12 minutes. The maximum value of COF at 15 minutes is approximately 1.2. Non-uniform and rough flank surfaces generated by wire-EDM for this ratchet gear are the reasons behind this instability and variation in COF. On the contrary, as shown in Fig 7b, the COF for the ratchet gear produced at optimum wire-EDM parameters is lesser, i.e., not more than 0.4, due to the superior flank surface characteristic with lesser roughness.

a)



b)

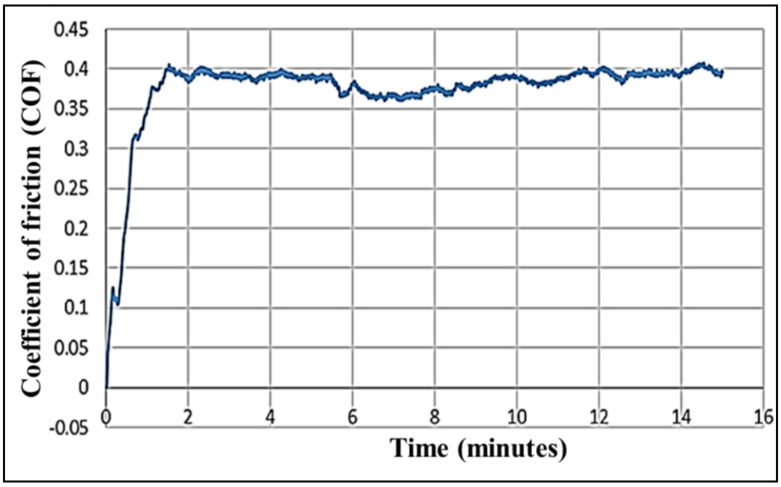


Fig. 9 Variation of COF with time during wear testing of wire-EDM manufactured miniature ratchet gears: (a) poor surface quality miniature ratchet gear; (b) optimized miniature ratchet gear

Figure 10 illustrates scanning electron microscopy (SEM) images of the miniature ratchet gear manufactured at optimum combination of wire-EDM parameter values. It can be confirmed that optimum gear has an even and precise profile of teeth and center-hole, and the tooth flank shows evenly distributed shallow craters and a smooth surface free from burrs and cracks.

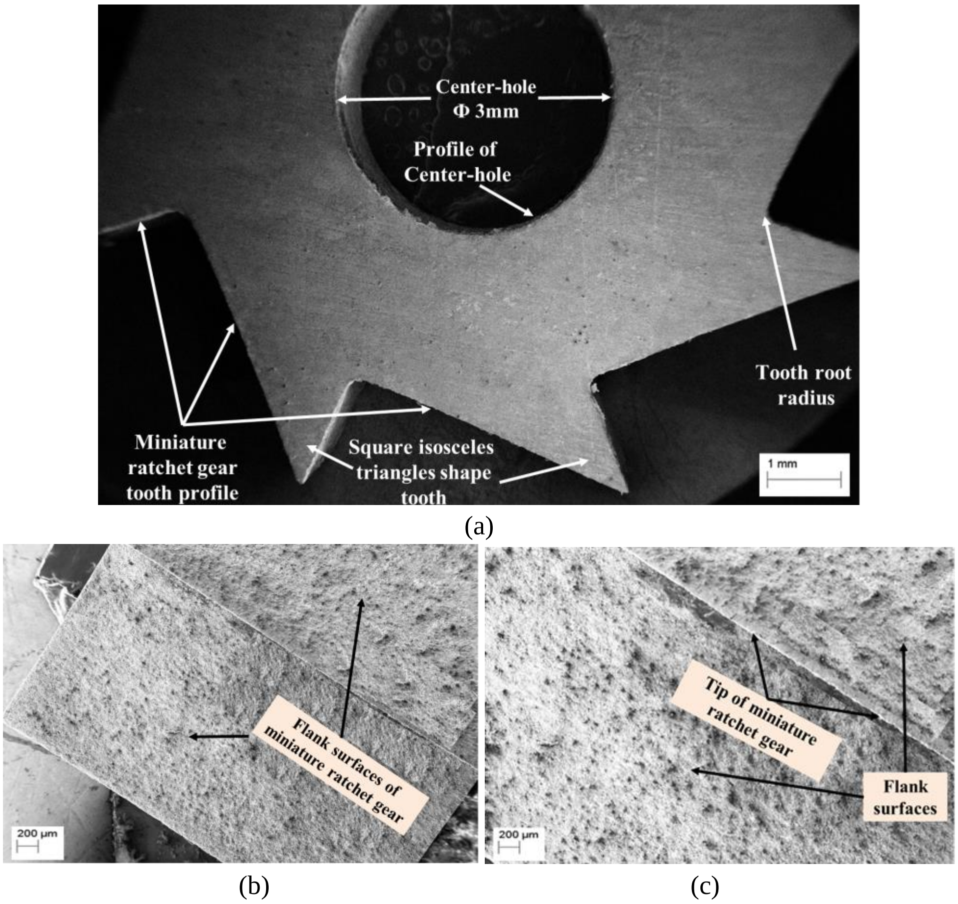


Fig. 10 Scanning electron micrographs of miniature ratchet gear manufactured at optimal parameters of wire-EDM: (a) gear teeth profile; (b) and (c) magnified flank surfaces

5. CONCLUSION

An investigation on successful fabrication of asymmetric miniature ratchet gears of stainless-steel is reported. A detailed study on mean roughness depth and material erosion speed along with the surface quality of ratchet gears is carried out. Some important conclusions from this research work are as follows:

- Based upon the analysis of variance study conducted on the experimental results, it is found that both spark duration and spark-off duration are the significant parameters, as their p values are less than 0.05. It is suggested to select both parameters carefully in wire-EDM when fabricating miniature gears of stainless-steel.
- Multi-objective optimization of wire-EDM, based on the desirability function analysis, resulted in flank surface roughness 5.30 µm and 6.75 mm/min material erosion speed at optimum parameter setting 1.5 µs spark duration, 42.5 µs spark-off duration, and 1500 g wire tension.
- Miniature ratchet gear machined at optimum wire-EDM parameters was found better in tribological performances with mean roughness depth R_z- 5.30 µm, coefficient of friction COF- 0.4, bearing length B_L- 81%, material portion Mr2-Mr1– 74.98% values much better than the selected gear machined under non-optimal regime that is having the tribology parameter values as R_z- 9.65 µm, COF- 1.2, BL- 78.6%, Mr2-Mr1- 68%.
- SEM study confirmed the absence of any burr, dirt, and cracks from the flank surfaces of the miniature ratchet gear machined at optimum parameters.
- This work is novel in the sense that it has explored and established wire-EDM as an alternate of conventional manufacturing processes for fabrication of miniature ratchet gears made of stainless-steel. It is hoped that the results of this detailed investigation on surface quality of the fabricated ratchet gears of stainless-steel and productivity of the wire-EDM process, would be helpful to the researchers and engineers to establish the field further.

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