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Sustainable Manufacturing of Asymmetric Miniature-Sized Ratchet Wheels by Wire Electrical Discharge Machining

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Abstract: In this paper, the outcomes of an investigation conducted on the sustainable manufacturing of asymmetric rotary miniature-sized ratchet wheels of stainless steel (SS) 304 by a vertically traveling wire electrical discharge machining (WEDM) process are reported. The consumptions of energy and wire material are the process sustainability indicators considered in this work. Box-Behnken-based seventeen experiments were conducted by varying spark-on-time 'T_{on}', spark-off-time 'T_{off}', and wire rigidity 'W_T'. Desirability function analysis (DFA) based on multi-response optimization was performed to obtain an optimum setting of WEDM parameters to manufacture miniature-sized ratchet wheels with minimum energy and wire consumption. Sustainable manufacturing of ratchet wheels is performed at the optimum parameter combination of T_{on}-1.5 µs; T_{off}-40.5 µs; W_T-1260 g, for the least values of energy consumption of 0.64 kWh and wire consumption of 20.11 g with no wire breakage and a significant reduction in total idle time. This ratchet wheel, manufactured at optimum parameters of WEDM, was also found to have a good finish (average surface roughness 'R_a'-1.08 µm and maximum surface roughness 'R_t'-6.81 µm) and defect-free tooth flank surfaces. Overall, it is concluded that WEDM has the potential to achieve sustainability in the manufacturing of miniature-sized ratchet wheels and other gears. The outcomes of this work will extensively facilitate engineers and researchers in selecting a suitable range of machining parameters for sustainable manufacturing of miniature-sized wheels and gears.

Keywords: energy consumption; miniature; ratchet wheel; sustainable manufacturing; wire electrical discharge machining

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1. Introduction

Sustainable manufacturing refers to the reduction in energy and resource consumption, and emission of hazardous by-products without compromising personnel health, safety aspects, and their impacts on the environment [1–3]. Nowadays, achieving them is of prime importance in manufacturing industries due to strict environmental regulations. It also affects manufacturing costs [4,5]. Estimation or calculation of energy and material consumption during the machining of customized parts and components is a challenging task due to the intricacy of manufacturing systems and the desirable flexible of operation [6]. Manufacturing by conventional machining processes prompts higher consumption of energy and raw materials for complex and intricate parts/components due to inherent limitations and requirements of secondary operations. This compels researchers to explore alternative manufacturing technologies and methods to produce precision parts and components with improved sustainability. Micro-pillars, micro-channels, microtubes, and miniature gears are some key components of many engineered systems. Their manufacturing quality is important, and thus the selection of appropriate processes is crucial.

A gear is a modified form of a wheel having teeth at equal spaces on its circumference to transmit motion and power between two shafts [7]. A ratchet wheel is an important mechanical element belonging to the gear family and is widely used to impart rotary or linear motion in one direction and prevent motion in the opposite direction [8]. Generally, miniature ratchet wheels are used in lifting devices and torque transmission systems to lock the motion in the opposite direction and stop reverse rotation when the input force is removed. The miniature-sized ratchet wheel is referred to as a low module (<1) wheel, whose diameter lies between 0.1 and 10 mm. Its quality directly affects the performance of the entire mechanism or system of miniature power tools and miniature lifting devices [9,10]. Forging, die-casting, blanking, powder metallurgy, and injection molding are the conventional processes for manufacturing miniature-sized ratchet wheels [10]. The inherent limitations of these processes, such as undesirable tool marks and machining challenges with high strength steel, wheel thickness, and achieving the desired accuracy with a single process, prompt the exploration of alternate manufacturing of ratchet wheels [11].

Vertically traveling wire electrical discharge machining (WEDM) is one of the widely used advanced machining processes for manufacturing miniature parts and components. This process has the capability to manufacture complex profiles and features from electrically conductive, difficult-to-machine materials [12–15]. In this process, the workpiece material is held on the working table with the help of clamps, and a very fine wire is fed through the upper guide, workpiece material, and lower guide. The wire and workpiece are partially or fully submerged in the continuously flowing deionized water and act as dielectric fluid. A direct electric current is supplied to create the electric sparks between the interelectrode gaps that will help to form the desired shape and size of the workpiece by melting and vaporizing unwanted materials from the workpiece [16–19]. The computerized numerical control (CNC) WEDM machine tool comes with a high degree of automation where stepper motors and pumps are used. It keeps the consumption of energy high. Frequent wire breakage, which prolongs the idle machining time, and high wire consumption are also some of the common issues in WEDM. These directly affect the WEDM process's sustainability.

There have been some past attempts to address the sustainability-related challenges and problems of the WEDM process and make it more sustainable. Some of them are discussed briefly in the following paragraph.

Gamage and DeSilva [20] studied wire breakage on process energy utilization and the environment during electrical discharge machining (EDM) of aluminum and steel plates. They concluded that wire failure significantly slows down the machining process and increases energy consumption and environmental footprints, which are unfavorable to production economics. Yang et al. [21] proposed a process model for energy consumption in the EDM process to produce holes. Fatima and Iqbal [22] identified energy requirements during machining on three different features of WEDM using molybdenum, brass, and copper wires, respectively, and reported the highest power consumption by coolant pump. Saharan et al. [23] developed a new cost performance index for the wire in WEDM considering the economic and ecological aspects. They identified the most suitable electrode wire with the help of a new performance index to achieve economical production and machining efficiency in WEDM.

It can be concluded from the past research work that interventions related to sustainability in the vertically traveling wire electrical discharge machining (WEDM) process are still in their infancy and further detailed investigations are needed for the sustainable manufacturing of miniature complex parts and components by this process and its variants. The authors attempt to make a contribution in this area by conducting the present experimental investigation where the vertically traveling WEDM process has been utilized to cut a miniature-sized ratchet wheel and process performance has been measured by energy and wire consumption to estimate the sustainability. The major objectives of this study are the following: to manufacture asymmetric miniature-sized ratchet wheels of SS 304 by the WEDM process with improved sustainability; to evaluate the energy and wire consumption during the manufacturing of miniature-sized ratchet wheels by the WEDM process; to avoid wire breakage and reduction in idle machining time to reduce energy as well as wire consumption; to study the effect of WEDM process parameters on energy and wire consumption during manufacturing miniature-sized ratchet wheels; to optimize the considered WEDM parameters with the objective to minimize energy and wire consumption during manufacturing miniature-sized ratchet wheels to enhance process sustainability.

2. Research Methodology

2.1. Materials Selection and Blank Development

Ferrous materials such as stainless steel are commonly used to manufacture gears for power transmission in extreme working environments due to their higher strength and capability to transmit medium to low power at moderate speed. In this study, the stainless steel 300 series was selected as a ratchet wheel material. A rectangular plate (Figure 1) of SS 304 of 5 mm thickness is used for cutting a miniature-sized ratchet wheel. The perfect flat top and bottom surfaces are necessary to achieve the uniform thickness of the rectangular plate; otherwise, it affects the performance of the WEDM for manufacturing miniature-sized ratchet wheels. Therefore, it becomes necessary to perform some machining and finishing operations to achieve the desired dimensions and surface finish of the wheel plate. Grinding and milling operations were performed to remove the excess materials from the top, bottom, and side surfaces of the plate. After that, buffing was performed to achieve the desired dimensions and smooth surface of the plate. In the next step, the array of microholes on the plate was machined by thermoelectric drilling (μ-TED) with the help of a rotating 0.8 mm diameter brass electrode. These micromoles serve as the passage of the vertically traveling wire of the WEDM for manufacturing miniature-sized ratchet wheels. Figure 1 depicts the schematic 3D views and detailed specifications of the rectangular plate with an array of microholes. The design and dimensions of the 8-teeth ratchet wheel are illustrated in Figure 2. Detailed specifications of a miniature-sized ratchet wheel are given in Table 1.

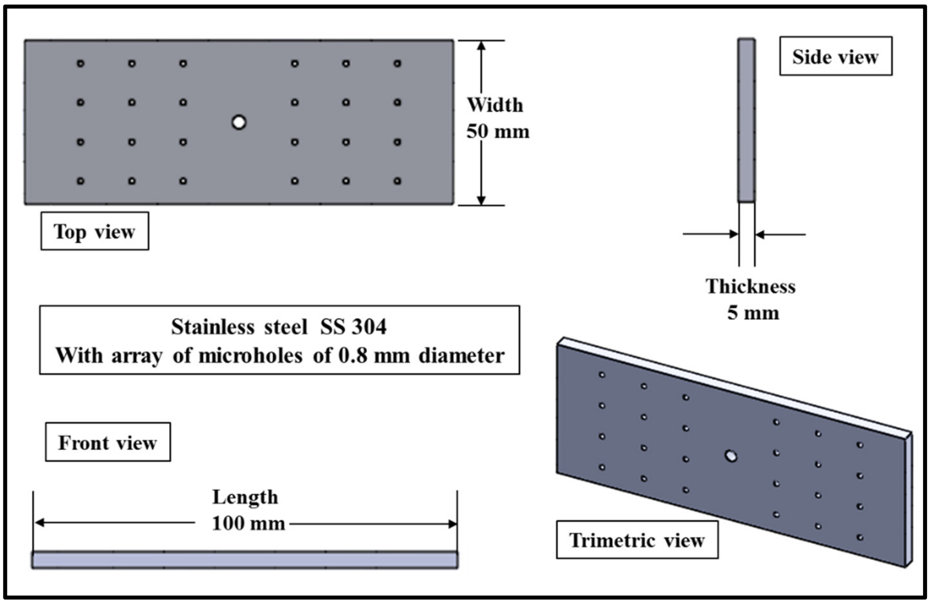


Figure 1. Detail specifications of the rectangular plate used for manufacturing miniature-sized ratchet wheels by WEDM.

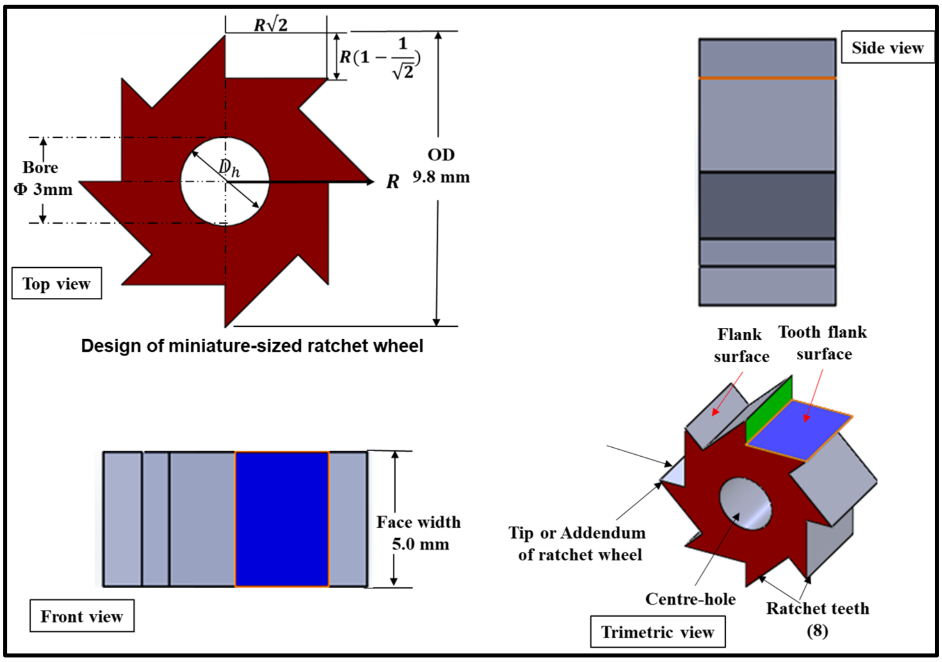


Figure 2. Design and dimensions of the proposed miniature-sized ratchet wheel.

Table 1. Details of process parameters, material composition, and ratchet wheel specifications.

WEDM Input Parameter				**Constant Parameters**
Name, 'Symbol' and (Unit)	**Coded Level**			
	−1	**0**	**1**	
Spark-on-time 'T_{on}' (µs)	0.9	1.3	1.7	***WEDM input parameters:*** *Peak current 'I_P': 12 A; Servo voltage 'S_V': 20 Volts; Wire speed: 4 m/min; Flushing pressure 'W_P': 15 kg/cm2; Cutting speed 'C_S': 100%* ***Electrode material:*** *Zinc coated wire; Wire diameter: 0.25 mm; Tensile strength: 800 N/mm^2;* ***Machining Medium:*** *Deionized water* ***Wheel materials and thickness:*** *SS 304 and 5 mm*
Spark-off-time 'T_{off}' (µs)	40.5	44.5	48.5	
Wire rigidity 'W_T' (g)	780	1140	1500	
Composition (% wt.) of Ratchet wheel material (SS 304)				
0.8% C; 6.8% Ni; 17% Cr; 1.2% Mn; 1% Si; 0.5% S; Balance Fe				
Ratchet wheel Specifications				
Material: SS 304; Profile: Involute; Addendum diameter: 9.8 mm; No. of teeth: 8; Face width: 5 mm; Bore/Center hole diameter: 3 mm				
Considered Responses				
Energy consumption (kWh) per ratchet wheel and wire consumption				
Parameters recorded during machining				
Voltage; current; power factor; machining time; weight of consumed wire; weight of ratchet wheel and plate weight				

2.2. Design and Development of Asymmetric Miniature-Sized Ratchet Wheel

In this study, asymmetric miniature-sized ratchet wheels were manufactured from the prepared SS 304 rectangular plate. Ratchet wheels whose outer diameter is less than 10 mm are commonly referred to as miniature-sized ratchet wheels. In terms of design, a miniature-sized ratchet wheel is an 8-teeth wheel having a structure based on a sequential organization of square isosceles triangles [24]. The radius of the ratchet wheel and center hole are R and DH, respectively, as shown in Figure 2. The center hole of a miniature-sized ratchet wheel reduces the weight and drag force of the wheel. The detailed dimensions of the miniature-sized ratchet wheel are illustrated in Figure 2.

In this study, non-submerged type computer numerical control (CNC) vertical traveling wires electrical discharge (also known as thermoelectric erosion) based machine tool

(Sprintcut, Electronica Pvt Ltd., Pune, Maharashtra, India) is used to cut these wheels from SS 304 rectangular plate using zinc-coated brass wire of 250 µm diameter having a tensile strength of 800 N/mm^2. The continuously flowing deionized water under pressure is used as dielectric to flush away the eroded particles from the interelectrode gap. The flexibility of this machine in terms of achieving an inclination angle of wire up to ±30° facilitated the production of tapered complex parts having dissimilar top and bottom profiles, i.e., ratchet wheels. The ELCAM software (version ELACM 1.0) inbuilt with the WEDM machine and developed by Electronica Machine Tools, Pune, India, is used to make a single-part program for making holes and manufacturing ratchet wheels.

Procedure for Development of Miniature-Sized Ratchet Wheel by WEDM

The procedure for manufacturing miniature-sized ratchet wheels by WEDM is discussed in this section. The sequences of the activities involved in manufacturing miniature-sized ratchet wheels can be categorized into four phases, namely (i) part-programming phase; (ii) preparation phase; (iii) machining phase; (iv) measurement phase. The sequence of phases and activities involved in manufacturing miniature-sized ratchet wheels are shown in Figure 3 and discussed as follows:

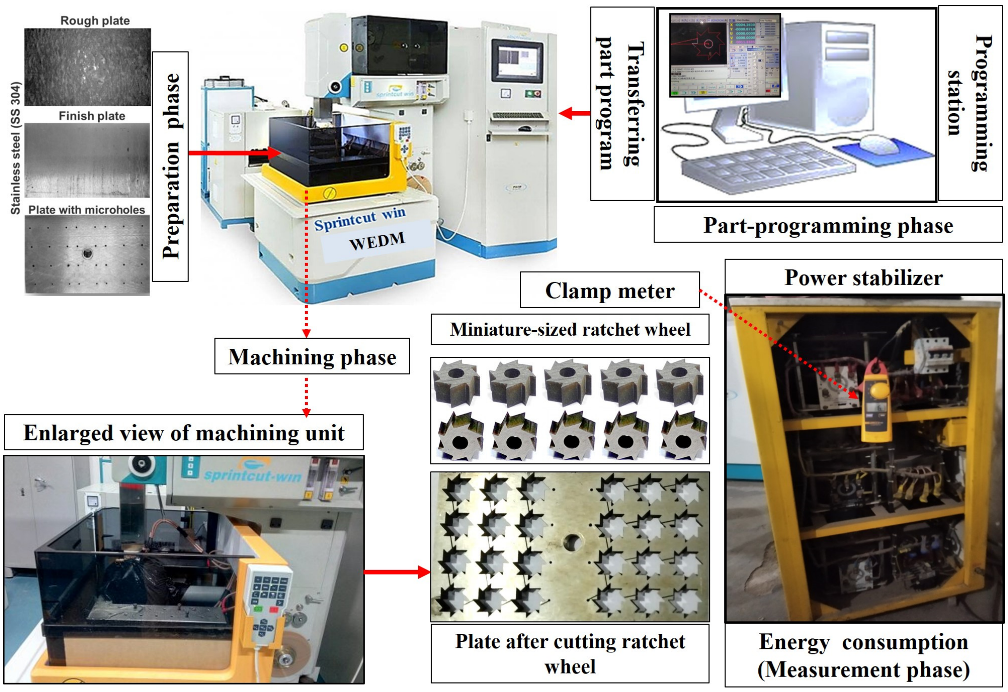


Figure 3. Different phases involved in the manufacturing of miniature-sized ratchet wheels by WEDM.

Part-programming phase

This is the initial phase, which involves drawing two-dimensional outlines for center hole and proposed miniature-sized wheel separately. Both were arranged in the same center using ELCAM software. The next activity of this phase is making part programs (G and M code based) for the center hole and then for the ratchet wheel separately and merging these programs into a single part program by ELCAM software followed by transferring them to the WEDM machine.

Preparation phase

This phase is idle, i.e., in this phase, no machining action takes place. The sequences of the several activities involves in this phase are (i) preparation of rectangular plate; (ii) drilling array of microholes of 0.8 mm diameter on the prepared plate by µ-TED (as discussed in Section 2.1); (iii) mounting of microhole plate on the worktable of WEDM machine (Figure 4). The flatness and stability of the rectangular plate were ensured using a dial gauge.

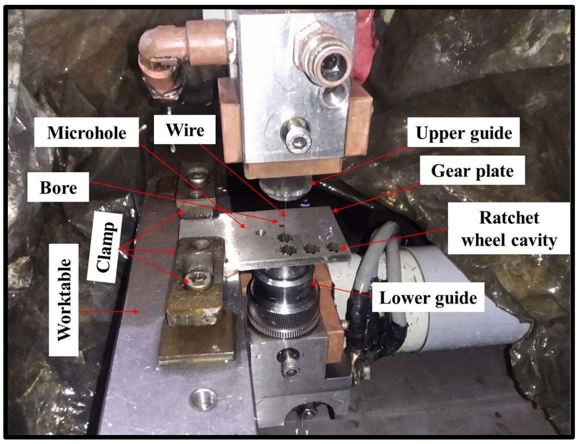


Figure 4. Closed view of machining chamber while manufacturing miniature-sized ratchet wheels by WEDM.

Machining phase

Several activities are involved in this phase to perform the cutting of miniature-sized ratchet wheels. The first activity is related to the placement and location of wire through and center of microhole. The next activity is making a center hole by enlarging the microhole (Figure 5). Thereafter, it is necessary to break the wire while the machine keeps running in a dry mode until the wire is located again at the adjacent microhole through which it is passed to cut a miniature-sized ratchet wheel according to the prepared part program. Cutting of ratchet wheels takes place by the movement of the working table of the CNC WEDM to locate the wire according to the path of papered ratchet wheel part program as shown in Figure 5. The three-dimensional views of manufactured miniature-sized ratchet wheels by the WEDM process are shown in Figure 6.

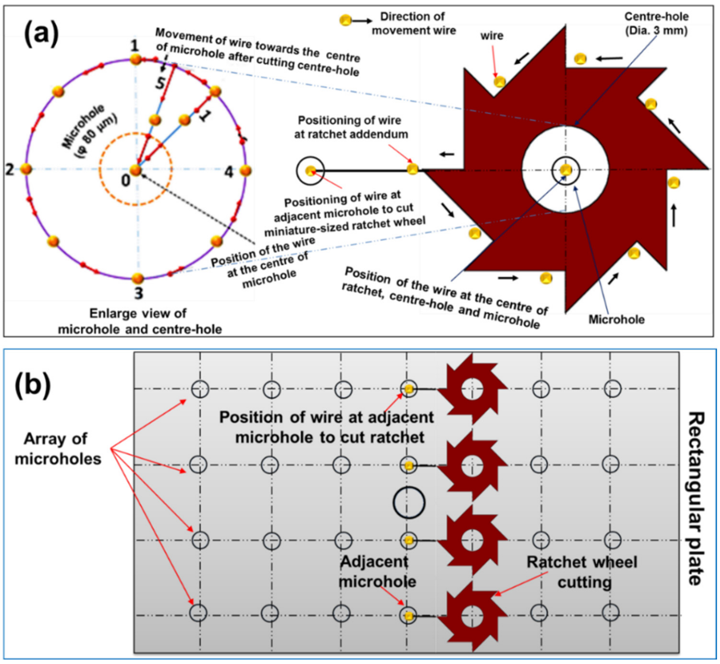


Figure 5. Layout of the miniature-sized ratchet wheel and rectangular plate: (**a**) direction of the wire movements during cutting of center hole and wheels by WEDM process; (**b**) schematic view of a plate with microholes.

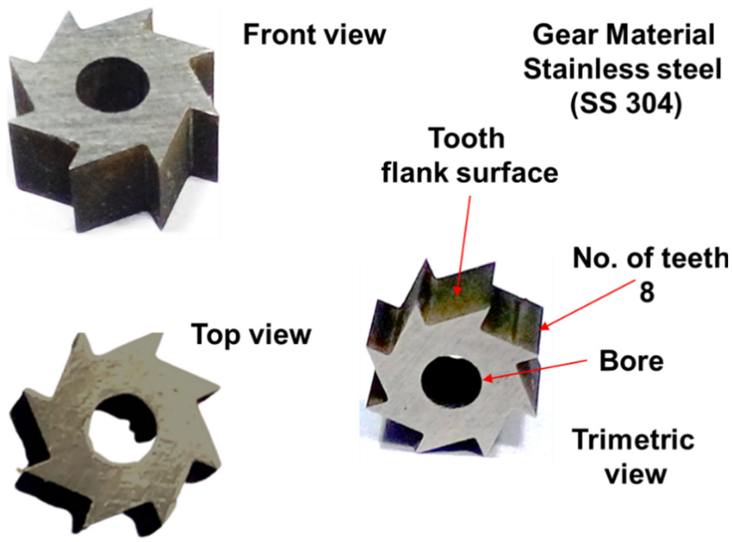


Figure 6. Original pictures of manufactured miniature-sized ratchet wheels made from SS 304 rectangular plate by WEDM process.

Measurement phase

Measurement of manufactured ratchet wheels is the final phase, in which measurements of current, voltage, power factor, and weight of consumed wire are taken place to calculate the energy and wire consumption during the manufacturing of miniature-sized ratchet wheels by WEDM.

2.3. Details of Experimentation

In this study, the Box–Behnken technique of response surface methodology (RSM) approach was used for designing and conducting seventeen experiments (with two replicates) by varying three WEDM process parameters, i.e., spark-on-time 'T_{on}'; spark-off-time 'T_{off}'; wire rigidity 'W_T' at three levels each while manufacturing miniature-sized ratchet wheels from SS 304 material. The details of the parameters and the chemical composition of SS 304 are given in Table 1. A spectrometer is used to determine the chemical composition of SS 304 (by weight) by the CLL-IDR-STP-BM-004 test method. The selection of parameters is based on machine constraints, some preliminary experiments, and literature. The details of the WEDM machine tool and software for part programming used in the present work have already been provided in Section 2.2.

2.4. Measurement of Selected Responses and Surface Quality

The cutting of ratchet wheels is the final phase of machining, in which measurements of current, voltage, and power factor were taken place to calculate the energy consumption during every single experiment conducted for manufacturing a miniature-sized ratchet wheel. In this study, a clamp meter (Fluke 362, 200A, AC/DC) and digital multi-meter (Fluke 101) were used to measure the current and voltage, respectively, during the cutting of each ratchet wheel and idle condition of the machine as shown in Figure 7. The available WEDM is equipped with a servo voltage stabilizer. Servo voltage stabilizer facilitates constant output voltage despite load current variations. While input and output voltages are noted directly from the display unit of the 3 φ servo voltage stabilizer fixed with the CNC WEDM machine. The clamp meter facilitates the measurement of the 3-phase output current (R, Y, and B) of the power stabilizer. Direct current (DC) is directly measured from CNC WEDM. Energy consumption was calculated using the following equation:

$$\text{Energy consumption } (P_E) = \frac{V \times I \times Cos\varphi}{1000} \times t \text{ (kWh)} \tag{1}$$

where, V stands for the input voltage to machine; I stands for DC supply to machine, φ stands for power factor, and t stands for time in hours.

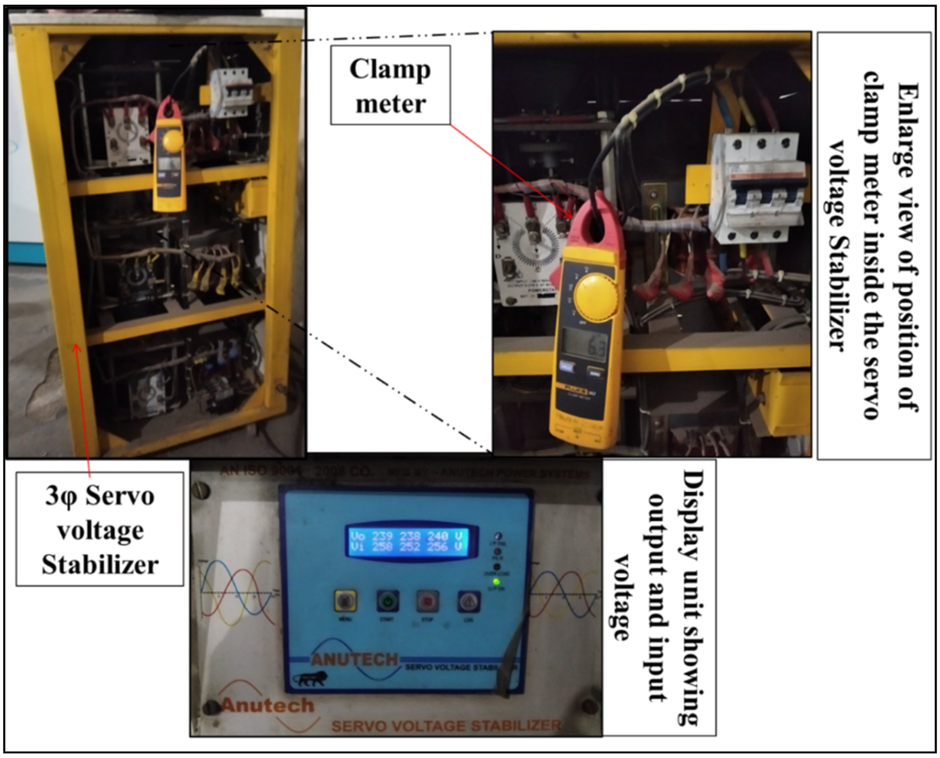


Figure 7. Measurement of energy consumption by clamp meter during manufacturing of miniature-sized ratchet wheels by WEDM.

In this study, the zinc-coated brass wire is used as electrode material for the cutting of miniature-sized ratchet wheels. Wire consumption was measured as the weight of wire in grams consumed during the cutting of miniature-sized ratchet wheels by WEDM. A precision weighing machine with 0.1 g accuracy was used for that. For ratchet wheel surface quality measurement, two instruments were used, scanning electron microscope, and a surface roughness tester. A scanning electron microscope made by Carl Zeiss (Oberkochen, Germany) was used to capture high magnification micrographs to analyze the tooth flank surfaces of the ratchet wheel. LD 130 3D surface roughness tester cum contour tracer instrument with a 2 µm diameter probe made by Mahr metrology (Göttingen, Germany) was used to measure surface roughness of ratchel wheel tooth flank. For surface roughness measurement, tracing by probe was performed across the wire cutting direction.

2.5. Multi-Response Optimization

The combination of response surface methodology, analysis of variance (ANOVA), and residual analysis, based study of experimental data found the existence of a quadratic model for both sustainability indicators, i.e., energy consumption and wire consumption. The statistical significance and fitness were evaluated by ANOVA and residual analysis, and the results are shown in Table A1 (Appendix A).

In machining processes, the appropriate selection of input parameters is essential to achieve a better quality of the manufactured products with improved productivity at minimum manufacturing cost [25]. Desirability function analysis (DFA) is an important and extensively utilized technique for the simultaneous optimization of multiple responses [26]. Equation (2) was used for the computation of desirability 'u_i' of all responses 'y_i' and then Equation (3) was used to estimate the total or combined desirability function 'U', which represents the geometrical mean of the desirability of the considered responses. In this study, responses considered for multi-response optimization using the DFA are classified as smaller-the-better, as both energy and wire consumption are required to be minimized to obtain a sustainable process.

$$u_i = \left(\frac{A - y_i}{A - S}\right)^{w_i} \tag{2}$$

$$U = (u_1\, u_2 \ldots\ldots u_n)^{\frac{1}{n}} = \left(\prod_{i=1}^{n} u_i\right)^{\frac{1}{\Sigma w_i}} \tag{3}$$

where,

S—objective value;

A—admissible upper limit;

w_i—relative importance or weightage assigned to the response $y_{i;}$

n—total number of responses.

An optimum machining combination is considered at the highest yielded value of the combined desirability [14].

A Design-Expert software is used to conduct ANOVA study, residual analysis, and DFA-based optimization.

3. Results and Discussion

Table 2 presents the values of the variable WEDM input parameters along with the corresponding values of considered responses for all the 17 experiments and their replications. The following empirical equations for energy and wire consumption have been developed through the response surface model:

Table 2. Combinations of process parameters for seventeen experiments with two replicates and corresponding average values of responses.

Run	WEDM Process Parameters			Ratchet Wheel							Bore							Pow-er Fact-or (φ)	Energy Consu-mption (kWh) 'P_E' Avg. R1 + R2	Wire Consum-ption (Grams) 'W_C' Avg. R1 + R2	Time (min) Avg. R1 + R2	Weight (gram) Avg. R1 + R2	
				Electrical Parameters																			
	Spark-on-time 'T_{on}' (µs)	Spark-off-time 'T_{off}' (µs)	Wire rigidity 'W_T' (g)	Voltage (239-41) (P-L)			Current (Ampere)				Voltage (Volts) (P-L)			Current (Ampere)									
				R	Y	B	R	Y	B	DC	R	Y	B	R	Y	B	DC					Ratchet	Bore
1	0.9 (−1)	40.5 (−1)	1140 (0)	240	239	240	6.5	6.5	5.6	1.2	240	239	240	6.5	6.5	5.6	1.2	0.99	1.07	34.74	14.68	1.67	0.13
2	1.3 (0)	44.5 (0)	1140 (0)	241	240	240	6.5	6.5	5.8	1.2	241	240	240	5.3	5.3	4.5	1.5	0.99	0.98	34.16	13.60	1.69	0.13
3	1.3 (0)	48.5 (1)	780 (−1)	239	240	240	6.5	6.5	5.7	1.4	239	240	240	6.5	6.5	5.6	1.5	0.99	1.07	41.90	14.42	1.64	0.12
4	0.9 (−1)	44.5 (0)	1500 (1)	241	241	239	6.4	6.4	5.6	1.3	241	241	239	6.2	6.2	5.6	1.3	0.99	1.67	50.50	22.93	1.67	0.12
5	1.7 (1)	44.5 (0)	780 (−1)	240	240	241	5.3	5.3	4.7	3.0	240	240	241	6.3	6.3	5.7	1.5	0.99	0.74	52.54	11.40	1.64	0.12
6	1.3 (0)	44.5 (0)	1140 (0)	241	241	239	6.1	6.1	5.3	2.0	241	241	239	6.1	6.1	5.2	2.0	0.99	0.84	32.99	12.17	1.64	0.12
7	1.3 (0)	40.5 (−1)	1500 (1)	241	240	241	6.2	6.2	4.9	2.1	241	240	241	6.4	6.4	5.9	2.1	0.99	0.74	23.35	10.60	1.62	0.13
8	1.3 (0)	44.5 (0)	1140 (0)	241	240	240	6.0	6.0	5.3	2.1	241	240	240	6.7	6.7	6.3	2.0	0.99	0.75	29.59	10.67	1.60	0.12
9	1.3 (0)	40.5 (−1)	780 (−1)	239	239	240	6.2	6.2	5.3	2.1	239	239	240	5.9	5.9	5.4	2.2	0.99	0.75	30.09	10.75	1.64	0.13
10	0.9 (−1)	48.5 (1)	1140 (0)	240	240	239	6.0	6.0	5.3	1.2	240	240	239	6.1	6.1	5.0	1.4	0.99	1.35	54.46	19.87	1.63	0.12
11	1.3 (0)	44.5 (0)	1140 (0)	241	240	240	6.0	6.0	5.3	1.9	241	240	240	6.0	6.0	5.3	2.0	0.99	0.87	34.36	12.75	1.64	0.13
12	1.7 (1)	40.5 (−1)	1140 (0)	239	241	240	6.2	6.2	5.5	3.2	239	241	240	6.1	6.1	5.4	3.1	0.99	0.69	25.01	9.75	1.64	0.12
13	1.7 (1)	44.5 (0)	1500 (1)	240	240	240	6.1	6.1	5.6	2.8	240	240	240	5.9	5.9	5.4	2.6	0.99	0.70	21.88	9.95	1.69	0.12
14	1.3 (0)	48.5 (1)	1500 (1)	241	240	240	6.7	6.7	6.1	1.8	241	240	240	5.9	5.9	5.4	1.8	0.99	1.11	31.05	14.72	1.70	0.12
15	1.3 (0)	44.5 (0)	1140 (0)	239	240	240	5.8	5.8	5.5	1.9	239	240	240	5.9	5.9	5.4	1.9	0.99	0.85	31.32	12.57	1.70	0.12
16	0.9 (−1)	44.5 (0)	780 (−1)	240	241	240	5.8	5.8	5.3	1.4	240	241	240	5.9	5.9	5.3	1.4	0.99	1.18	49.76	17.67	1.68	0.13
17	1.7 (1)	48.5 (1)	1140 (0)	239	240	240	5.8	5.8	5.5	2.1	239	240	240	5.6	5.6	5.6	2.1	0.99	0.84	31.29	12.53	1.69	0.12

For energy consumption

$$\begin{aligned}&\text{Energy consumption } {}'P_E{}' \\ &= +0.86 - 0.29\ T_{on} + 0.14\ T_{off} + 0.06\ W_T + 0.14\ T_{on}^2 - 0.013\ T_{off}^2 + 0.072\ W_F^2 \\ &-0.032\ T_{on}T_{off} - 0.13\ T_{on}W_T + 0.12\ T_{off}\ W_T\end{aligned} \tag{4}$$

For wire consumption

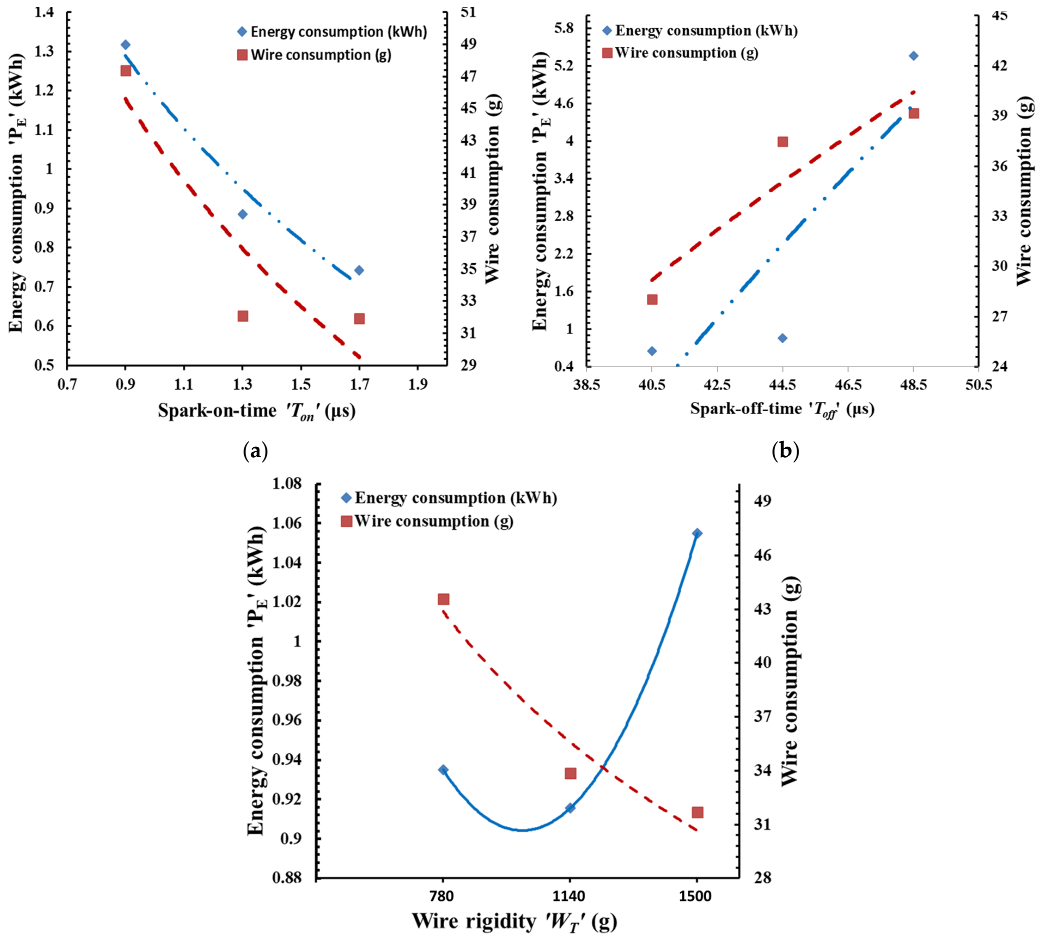
$$\begin{aligned}&\text{Wire consumption } {}'W_C{}' \\ &= +32.48 - 7.72T_{on} + 5.56\ T_{off} - 5.94\ W_T + 7.61\ T_{on}^2 - 4.47T_{off}^2 + 3.58\ W_F^2 \\ &-3.61\ T_{on}T_{off} - 7.85\ T_{on}W_T - 1.03\ T_{off}\ W_T\end{aligned} \tag{5}$$

The ANOVA analysis, as presented in Table A1, can be summarized as follows:

- T_{on}, T_{off}, and the interaction between T_{on} and W_T, and squared terms of T_{on} were found significant for the energy consumption;
- T_{on}, T_{off}, and W_T, and their squared terms were found significant for wire consumption;
- Interactions between T_{on} and T_{off} and T_{on} and W_T were found significant for the wire consumption. The F-value for the developed models indicates the 2nd order polynomials based on RSM are significant;
- *p*-values of the developed models are less than 0.05, indicating that developed models are significant. Non-significant *lack of fit* is desirable;
- It can be seen from Table A1 that the *lack of fit* tests of the developed models are not significant (i.e., *p*-values are greater than 0.05) relative to the pure error. The values of PRESS are 1.07 for energy consumption and 592.24 for wire consumption. The values of R-Squared are 0.9188 for energy consumption and 0.9702 for wire consumption (i.e., close to 1), which confirm the adequacy of the developed models. Adequate precision of the developed models indicates the signal-to-noise ratio, and a ratio greater than 4 is desirable. It can be confirmed from Table A1 that the values of adequate precision are more than 4 for the developed models; thus, models indicate adequate signal.

Figure 8 shows the variation of energy consumption and wire consumption with spark-on-time 'T_{on}'; spark-of-time 'T_{off}'; wire rigidity 'W_T'. It can be seen from Figure 8a that (i) energy consumption (kWh) and wire consumption decrease linearly with an increase in the values of spark-on-time. It can be observed from Figure 8b that energy consumption (kWh) and wire consumption increase linearly with an increase in the values of spark-off-time. These trends can be explained by the fact that longer spark-on time increased the time duration of generated sparks transferring between the interelectrode gaps, which, consequently, increased the amount of material removed from the work surface in a given time, thus reducing the total cutting time to produce a miniature-sized ratchet wheel. This reduction in total cutting time resulted in a low consumption of wire and energy. On the other hand, a longer spark-off-time increased the duration in which no sparks were generated between the interelectrode gaps. Thus, a longer spark-off- time extended the cutting time to produce a miniature-sized ratchet wheel. Hence, energy and wire consumption are higher.

It is evident from Figure 8c that wire consumption decreases with an increase in wire rigidity, whereas energy consumption decreases to an optimum value and then increases with an increase in wire rigidity. At higher values of rigidity, the wire remained straight between the interelectrode gaps and thus maintained a certain distance with the workpiece to avoid short-circuiting and blockage when removing particles from the interelectrode gap. Short-circuiting causes interruption during the cutting of miniature-sized ratchet wheels and leads to excess wire consumption and energy consumption with no machining action taking place during short-circuiting. Higher wire rigidity (after optimum value) formed a neck shape at the point of the wire, which came in contact with sparks that slightly increased the interelectrode gap and resulted in a slight increase in energy consumption.



(**a**) (**b**)

(**c**)

Figure 8. Variation of sustainability indicators with (**a**) spark-on-time; (**b**) spark-off-time; (**c**) wire rigidity.

It is worth mentioning that short-circuiting occurs when the wire comes into contact with the workpiece. It happens due to wire vibration, which mainly occurs at a low level (below 420 g) of rigidity at high flushing pressure. However, high flushing pressure is desirable to remove the eroded particles from the machining zone or interelectrode gap, especially in miniature gear/wheel cutting. Moreover, higher values of wire rigidity are also desirable to achieve better dimensional accuracy of ratchet wheels and gears. Thus, it becomes necessary to keep the higher value (at a certain range, i.e., selected range) of wire rigidity to perform ratchet wheel cutting with better dimensional accuracy and without wire breakage.

Figure A1 presents the residual analysis graphs for energy consumption (kWh) and wire consumption (g). It is evident from Figure A1a,b that all of the residuals are gathered around a straight line; thus, it can be proven that these residuals are normally distributed for energy consumption and wire consumption during the manufacturing of miniature-sized ratchet wheels by WEDM.

As mentioned before, desirability function analysis was used to find the optimum machining combinations of WEDM variable parameters, considering both responses, i.e., energy consumption and wire consumption, of miniature ratchet wheels as smaller-the-better type characteristics and allocating equal importance to them. Thus, we assigned a weightage of 0.5 to each response of miniature ratchet wheels, and the following equations are used to calculate their desirability for the *i*th combination of WEDM variable parameters as follows:

For energy consumption

$$(u_{P_E i}) = \left[\frac{P_{E\,max} - P_{E\,i}}{P_{E\,max} - P_{E\,min}}\right]^{0.5} \tag{6}$$

For wire consumption

$$(u_{W_C i}) = \left[\frac{W_{C\,max} - W_{C\,i}}{W_{C\,max} - W_{C\,min}}\right]^{0.5} \tag{7}$$

where, $P_{E_{min}}$, $W_{C_{min}}$, $P_{E_{max}}$, $W_{C_{max}}$ are the minimum and maximum values of total energy consumption and total wire consumption during the manufacturing of miniature ratchet wheels by the WEDM process.

The minimum values used for total energy consumption (P_E) and total wire consumption (W_C) are 0.69 kWh and 21.88 g, respectively, while the corresponding maximum values are 1.67 kWh and 54.46 g, respectively. Equation (8a,b) has been used to compute the overall desirability function 'U_i' for the ith combination of WEDM parameters as follows:

$$U_i = \left[\left\{\left(u_{P_E}\right)_i\right\}^{0.5}\left\{\left(u_{W_C}\right)_i\right\}^{0.5}\right]^{\frac{1}{0.5+0.5}} \tag{8a}$$

$$U_i = \left[\left(u_{P_E}\right)_i\left(u_{W_C}\right)_i\right]^{0.5} \tag{8b}$$

3.1. Validation of the Optimized Results

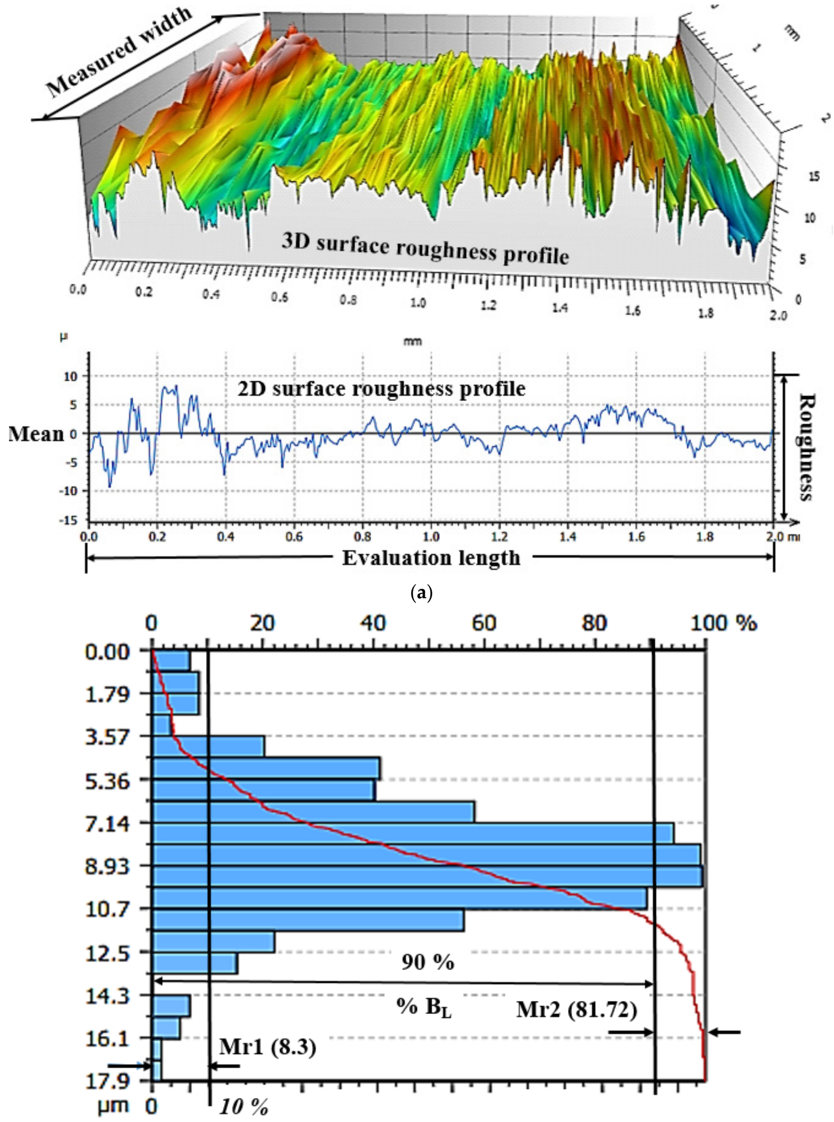
The desirability prediction for optimization has been verified by conducting confirmation experiments. The standard values of variable parameters of the WEDM machine nearest to the corresponding optimized values (predicted by desirability) were used for the confirmation experiments. Two confirmation experiments were conducted at optimized values of the WEDM variable parameters. Table 3 presents optimized values of the WEDM variable parameters and sustainability indicators as predicted by desirability function analysis and results of confirmation experiments after cutting ratchet wheels on optimum parameters. It can be observed from Table 3 that the total energy consumption and total wire consumption during manufacturing miniature ratchet wheels are 0.65 kWh and 20.25 g, respectively (average of confirmation experiments R1 and R2). Thus, the values of total energy consumption and total wire consumption during manufacturing miniature-sized ratchet wheels reveal very good agreement between the desirability predictions and validation results, with 4.4% and 2.5% differences. It can be said that the desirability function analysis has successfully optimized WEDM parameters and minimized energy and wire consumption. This consequently improved the sustainability of the WEDM process for ratchet wheel manufacturing.

Table 3. Desirability function analysis-based predictions for optimization and results of confirmation experiments.

Details	Name	By DFA	Experimental Validation (i.e., Corresponding Values Avialble in the M/C)		Difference
			R1	R2	
Optimum values of WEDM variable parameters	T_{on} (µs)	1.49	1.5		
	T_{off} (µs)	40.53	40.5		
	W_T (g)	1259	1260		
Optimum values of responses	P_E (kWh)	0.69	0.66	0.64	0.03 (−4.4%)
	W_C (g)	20.62	20.11	20.29	0.41 (−2.5%)
Machining time in Minutes			9.4	9.6	

3.2. Surface Quality of Ratchet Wheel

Figure 9 shows the results of the 3D surface roughness parameters measurement of the flank surface of the miniature-sized ratchet wheel manufactured at optimum parameters of WEDM. Surface roughness parameters such as average and maximum roughness (R_a and R_t), and material ratio or Abbott–Firestone parameters are responsible for wear characteristics and tribology performance of ratchet wheels and gears [7,10]. It is found that the ratchet wheel has a average roughness of R_a-1.08 µm and a maximum roughness of R_t-6.81 µm. Figure 9a presents the 3D and 2D surface roughness profile distribution. The Abbott–Firestone or bearing area curve (BAC) for the ratchet wheel, as presented in Figure 9b, confirms its tribological fitness due to the availability of a significant amount of surface material (Mr_2-81.7%) for its lifecycle usage. It will protect this ratchet wheel from early wear and tear and failure when it rotates to match with other wheels during application.



(**a**)

(**b**)

Figure 9. The 3D surface roughness measurements of miniature-sized ratchet wheel manufactured by WEDM using optimal machining parameters: (**a**) 3D and 2D surface roughness profiles; (**b**) Abbott–Firestone curve.

Figure 10a–c illustrates scanning electron micrographs (SEM) of the ratchet wheel, Uniform tooth profiles and bores, and burr- and crack-free tooth surfaces are evident from the micrographs.

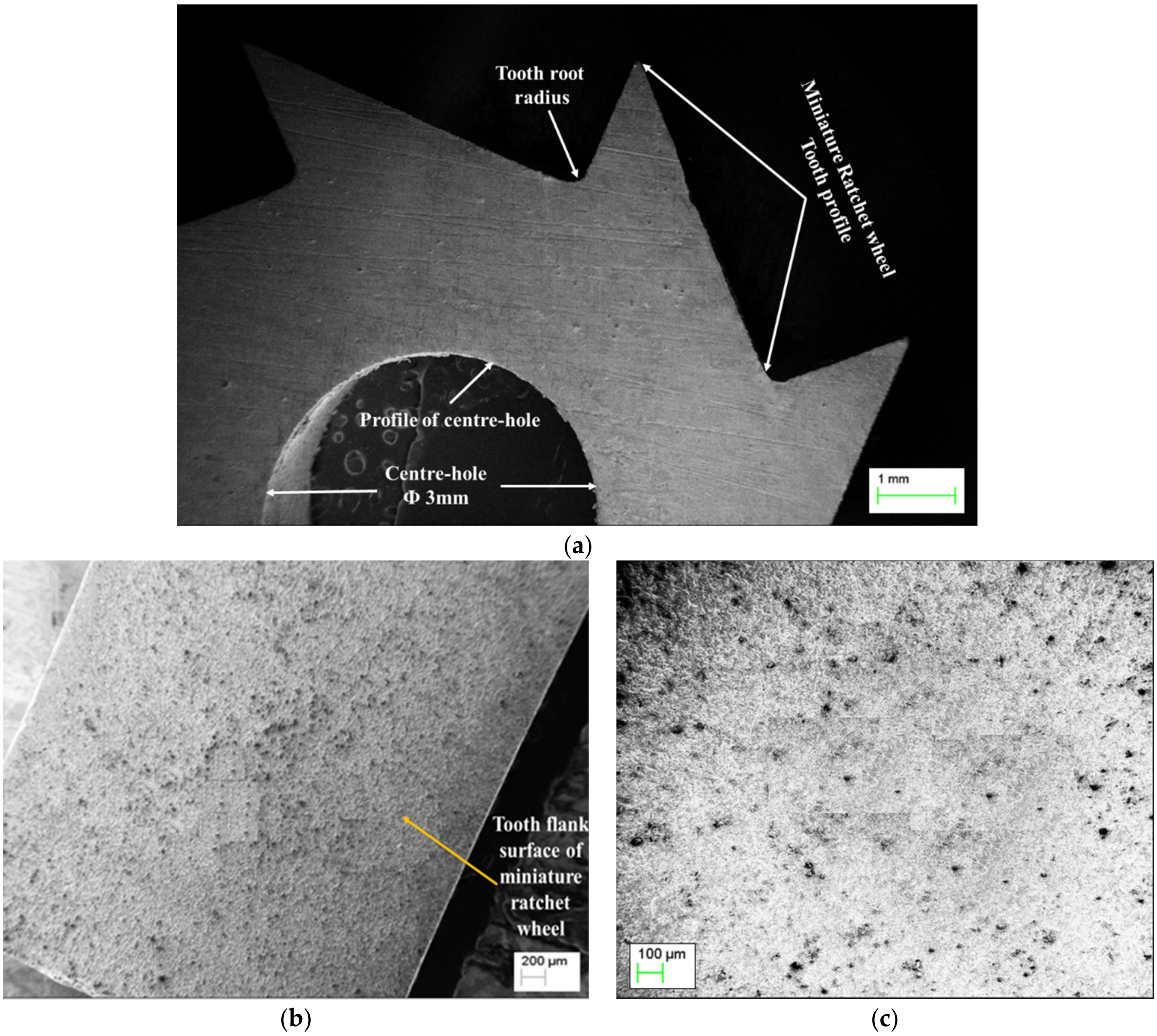


Figure 10. SEM micrographs of miniature-sized ratchet wheel manufactured at optimal parameters of WEDM: (**a**) bore/center hole and tooth profile; (**b**,**c**) flank surface.

The surface quality of the ratchet wheels produced in the present work is found to be superior to those manufactured by other researchers in the previous work using Artemia-driven and migratory phytoplankton with phototaxis stimulus-based processes [24,27]. The surface finish (R_a 1.08 μm) of the SS 304 miniature ratchet wheel manufactured by WEDM in the present work is better than the surface finish (R_a 2.4 μm) of the miniature spur gears made from EMS 45 steel by the WEDM process [28]. The ratchet wheel manufacturing conducted in the present work is found more efficient, for energy and resources, than previous studies conducted on stainless steel gear manufacturing by WEDM [29]. An observation of the present study, which the energy consumption is mostly affected by spark-on-time, is in agreement with the study on the machining of EN31 steel by the WEDM and reported in [30].

4. Conclusions

Miniature-sized ratchet wheels are successfully manufactured by vertically traveling wire electrical discharge machining (WEDM) in the present work. Detailed analysis and optimization of process parameters for energy and wire consumption have been conducted. The major conclusions from this research work are as follows:

- Manufactured SS 304 miniature-sized ratchet wheels of 1.62 g each by WEDM for lightweight applications;
- The park-on-time and spark-off-time are significant parameters that largely affect energy and wire consumption during the manufacturing of miniature-sized ratchet wheels by the WEDM process;
- Wire rigidity is also a significant parameter that only affects the energy wire consumption during the manufacturing of miniature-sized ratchet wheels by the WEDM process;
- During the WEDM of 17 miniature-sized ratchet wheels:
- −16.19 kWh of total energy was consumed, which makes an average of 0.95 kWh for a single ratchet wheel;
- −608.99 g of zinc-coated brass wire was consumed and 35.76 g of wire was consumed for every single ratchet wheel manufactured. It can be concluded that the tool material loss during machining is less, and thus has less impact on the working environment and operators' health;
- −30.28 g of work material was eroded, out of which 11.8 g of work material was consumed for manufacturing each miniature-sized ratchet wheel. It can be concluded that the maximum utilization of wheel plate (blank) material can be achieved by WEDM;
- Desirability function analysis-based optimization for WEDM of ratchet wheels at optimum parameters' combination of 1.5 μs spark-on-time, 40.5 μs spark-off-time, and 1260 g wire rigidity resulted in the least energy consumption of 0.64 kWh and a wire consumption of 20.11 g, which enhanced the sustainability of the process;
- The desirability predicted and actual validated values of total energy consumption and total wire consumption, are in close agreement with 4.4% and 2.5% errors, respectively;
- Good surface quality with defect-free tooth surfaces of the ratchet wheel and 1.08 μm average roughness and 6.81 μm maximum flank surface roughness, governs the tribological fitness of the gear obtained at optimum parameters of WEDM.

Author Contributions: Conceptualization, experimentation, measurement, analysis, optimization and validation, writing–original draft and carrying out revision, S.K.C.; conceptualization, analysis, supervision, revision, and editing, K.G. All authors have read and agreed to the published version of the manuscript.

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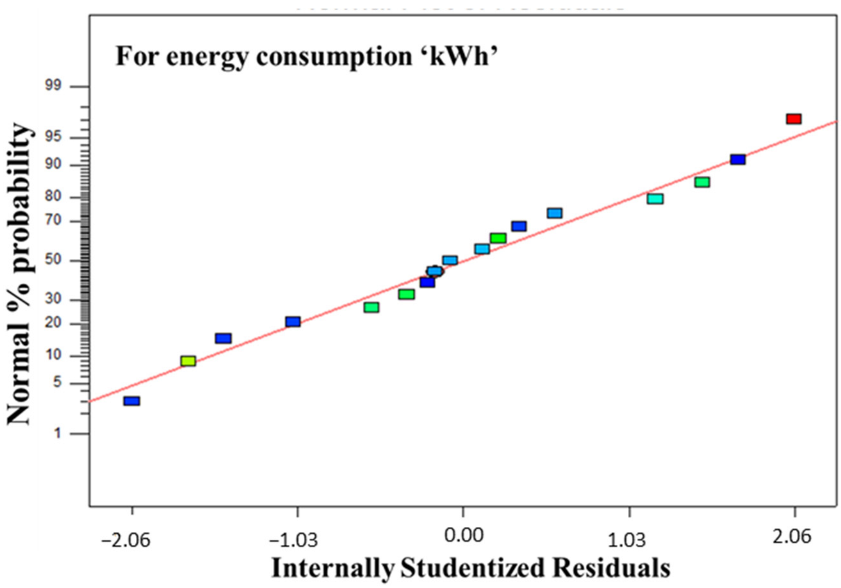
Conflicts of Interest: The authors declare no conflict of interest.

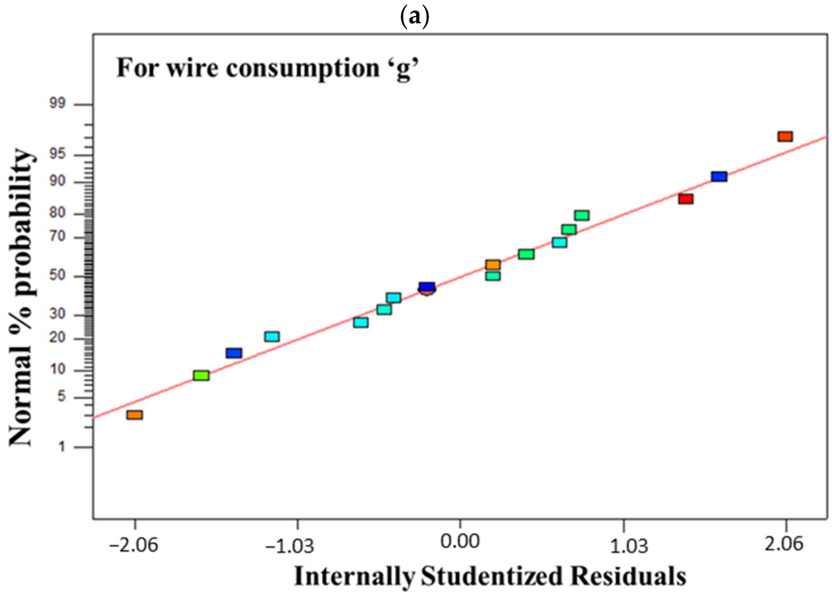
Appendix A

Table A1. Results of ANOVA for energy and wire consumption during the manufacturing of miniature-sized ratchet wheels by WEDM.

Source	Sum of Squares	DF	Mean Square	*F*-Value	*p*-Value	Remarks
For Energy Consumption 'P_E'						
Model	1.03	9	0.11	8.80	0.0045	Significant
T_{on}	0.66	1	0.66	50.65	0.0002	Significant
T_{off}	0.16	1	0.16	12.01	0.0105	Significant
W_T	0.029	1	0.029	2.21	0.1810	Not significant
$T_{on}\ T_{off}$	4.225×10^{-003}	1	4.225×10^{-003}	0.32	0.5872	Not significant
$T_{on}\ W_T$	0.070	1	0.070	5.38	0.0534	Significant
$T_{off}\ W_T$	6.250×10^{-004}	1	6.250×10^{-004}	0.048	0.8330	Not significant
$(T_{on}{}^2)$	0.085	1	0.085	6.53	0.0378	Significant
$(T_{off}{}^2)$	6.845×10^{-004}	1	6.845×10^{-004}	0.052	0.8254	Not significant
$(W_T{}^2)$	0.022	1	0.022	1.68	0.2356	Not significant
Residual	0.091	7	0.013			
Lack of fit	0.064	3	0.021	3.17	0.1474	Not significant
Pure error	0.027	4	6.770×10^{-003}			
Cor Total	1.13	16				
R-Squared = 0.9188, Adjusted R-Squared = 0.8144, Predicted R-Squared = 0.0482						
PRESS = 1.07, Adequate Precision = 10.955						
For Wire Consumption 'W_C'						
Model	1682.21	9	186.91	25.29	0.0002	Significant
T_{on}	476.48	1	476.48	64.47	<0.0001	Significant
T_{off}	247.64	1	247.64	33.51	0.0007	Significant
W_T	282.15	1	282.15	38.18	0.0005	Significant
$T_{on}\ T_{off}$	52.13	1	52.13	7.05	0.0327	Significant
$T_{on}\ W_T$	246.49	1	246.49	33.35	0.0007	Significant
$T_{off}\ W_T$	4.22	1	4.22	0.57	0.4744	Not significant
$(T_{on}{}^2)$	243.63	1	243.63	32.96	0.0007	Significant
$(T_{off}{}^2)$	83.97	1	83.97	11.36	0.0119	Significant
$(W_T{}^2)$	53.94	1	53.94	7.30	0.0306	Significant
Residual	51.74	7	7.39			
Lack of fit	35.42	3	11.81	2.89	0.1655	Not significant
Pure error	16.31	4	4.08			
Cor Total	1733.94	16				
R-Squared = 0.9702, Adjusted R-Squared = 0.9318, Predicted R-Squared = 0.6584						
PRESS = 592.24, Adequate Precision = 15.432						



(**a**)



(**b**)

Figure A1. Normal probability distribution graphs of residuals for considered responses: (**a**) energy consumption 'P_E'; (**b**) wire consumption 'W_C'.

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