Optimization of process parameters during WEDM of EN-42 spring steel

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Received: 11 July 2019 / Accepted: 30 March 2020 / Published online: 23 April 2020
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Abstract

The present work aimed to carry out the machining of EN-42 spring steel in wire electrical discharge machining with zinc-coated brass wire using distilled water as a dielectric medium. The effect of WS_2 powder added in a dielectric medium, on the metal removal rate and surface roughness has been evaluated. With the use of WS_2 , the conductivity of the dielectric is found to be constantly equal to 10 S/m, which is a very promising feature. WS_2 enhances dielectric life, metal removal rate, and surface roughness significantly. The effect of cryogenically treated wire on the metal removal rate and surface roughness during machining has been carried out. Taguchi method and genetic algorithm were used to optimize machining performance measures. Both methods provide optimum parameters and target value. The results of the Taguchi method show more error as compared to the genetic algorithm. The on time can be predicted as the most significant parameter according to the Taguchi method. From the results, it is observed that higher on time shows better metal removal rate and lower on time shows a better surface finish.

Keywords Cryogenic treatment · Metal removal rate · Root mean square surface roughness · Taguchi · S-method · Genetic algorithm · EN-42 spring steel

Abbreviations

EDM	Electrical discharge machining
TWR	Tool wear rate
ASTM	American society for testing and materials
S/N	Signal to noise ratio
WEDM	Wire electrical discharge machining

Notations

T_{on}	On time, μ S
T_{off}	Off time, μ S
F_{wf}	Wired feed, M/min
F_{sf}	Servo feed, M/min
MRR	Material removal rate, m^3/min

1 Introduction

Wire electrical discharge machining (WEDM) process can be used to machine metal (soft or hard) with good dimensional accuracy with the help of electrical spark formed between the workpiece and the electrode which is in the shape of the required contour. The WEDM is the thermal non-conventional method used for complex shape material's machining. The electric discharge or spark erosion of the metallic electrode (positive and negative charge) is the basic principle of electrical discharge machining (EDM). The tool's active part is immersed entirely in a fluid

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s42452-020-2650-2>) contains supplementary material, which is available to authorized users.

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SN Applied Sciences (2020) 2:947 | <https://doi.org/10.1007/s42452-020-2650-2>

medium known as a dielectric which is non-conductive. The electric discharge or spark erosion for cutting takes place under the blanket of dielectrics such as mineral oil or kerosene fed to the container in which EDM takes place. The removed particles are getting flushed away with dielectric fluid flow [1–5].

Jeswani [6] investigated the comparison of MRR and root mean square surface roughness in electrical discharge machining by using distilled water and kerosene as dielectric fluids. He found that the MRR was higher and the tool wear rate was lower for the case where distilled water was used as dielectric fluid as compared to that of kerosene. Rao et al. [7] studied the surface integrity of WEDM on aluminum 2014 T6 alloy. They suggested that better surface integrity was achieved at lower levels of a pulse on time (T_{on}) and peak current along with higher values of spark gap voltage. König and Siebers [8] investigated the effect of water as a dielectric fluid in the EDM process. They found that higher thermal stability results in greater MRR. The large pulse duration, higher pulse duty factor and discharge current also have a considerable effect on material removal rate.

Leão and Pashby [9] reported that the organic compound like ethylene glycol, polyethylene glycol-200,400,600; dextrose and sucrose improves the performance of deionized water as the dielectric fluid. Chow et al. [10] investigated the effect of pure water and a SiC powder combination as a dielectric fluid in micro-slit EDM for machining Ti alloy. The pure water and a SiC powder could disperse the discharging energy which results in better root mean square surface roughness and higher material removal rate (MRR) simultaneously as compared to that of pure water. The graphite powder [11, 12], tungsten powder [13] (a grain sizes in the range of 1 μm and 100 μm) mixed dielectric fluids in the application of EDM process shows the improved surface quality of the workpiece, higher MRR and lower tool wear rate.

The surface quality or root mean square surface roughness during any machining process depends on operating process parameters [14, 15]. Kumar et al. [16] reported a study on the working process of WEDM by using two different dielectric fluids on HCHCr alloy steel. They found that when copper powder suspended in the demineralized water used as dielectric gives higher MRR and lower root mean square surface roughness. Khan et al. [17] investigated the effect of alumina powder added in dielectric during the electrical discharge machining process. They concluded that the presence of powder in the dielectric increases the MRR and tool wear rate (TWR) but higher concentrations of powder gives better the root mean square surface roughness.

Prihandana et al. [18] investigated the effect of the dielectric fluid on MRR and surface quality in the EDM process. They used suspended micro- Molybdenum Disulfide (MoS_2)

powder in a dielectric fluid and applied ultrasonic vibration during micro-EDM processes. They found that the combination of MoS_2 powder and ultrasonic vibration significantly increased the material removal rate and improves surface quality. Yan et al. [19] investigated the influence of urea which was added into the distilled water as the dielectric medium for machining titanium on EDM. The work surface shows improved friction and wears characteristics, and the MRR and TWR decreases as the pulse duration increases.

Jain and Adhikary [20] reported that the polarity of the electrode and workpiece affects the MRR and surface finish of the machined surface. Amorim et al. [21] investigated the effect of Molybdenum powder mixed in the dielectric fluid on surface modification of AISI H₁₃ tool steel by EDM. They reported that the enrichment of the recast layer has increased hardness as compared to the metal matrix. Haşçalık and Çaydaş experimentally studied the WEDM of AISI D5 tool steel and they found that the root mean square surface roughness, amount of recast and micro-cracking have been affected by the process energy i.e. as the magnitude of input energy on the surface increases, it increases the thickness of the heat-affected zone. The surface roughness increases as the pulse duration increase. The dielectric fluid pressure and speed of wire also has not much influence on machining [22].

Kumar and Bhatia [23] experimentally proved that the Cryo-treated brass wires used in WEDM are improved the root mean square surface roughness as compared to not untreated H-11 die steel. Gaikwad and Jatti [24] reported the MRR during EDM of cryogenic-treated NiTi alloys. They concluded that the input parameters such as workpiece electrical conductivity, gap current, and pulse on time have a significant effect on material removal rate. Sharma et al. [4] cryogenically treated tool steel (AISI D3) workpiece with a different parameter like wire feed rate, time between two pulses, pulse width and mechanical wire tension on MRR and root mean square surface roughness and they found good MRR and surface finish for cryogenically treated wire with zinc coating. Kapoor et al. [25] cryogenically treated a brass wire with zinc coating and they also found there is an increase in MRR with cryogenic treatment. Goyal found that the current and pulse on time are the important factor which affects the MRR and root mean square surface roughness in his experiment of EDWM with cryogenically treated electrode tool.

There are various conclusions that can be drawn from the present literature i.e. Tungsten sulfide (WS_2) nano powder has good lubrication properties like MoS_2 , but yet it has not been used in powder mixed WEDM. The cryogenic treatment has been used as an effective process which is basically implemented to improve wear resistance. Its combination with WS_2 powder has a promising scope. Taguchi method has been widely used for the optimization

of WEDM parameters; however genetic algorithm has been given less attention in past research.

In this study, the machining of EN-42 spring steel in wire EDM with zinc-coated brass wire has been carried out using distilled water as a dielectric medium. This study is focused on optimizing the input parameters (on time, off time, wire feed, servo feed) using the Taguchi method and Genetic algorithm and also to obtain optimum metal removal rate and root mean square surface roughness using Taguchi method and genetic algorithm and confirming them with experimental results. The effect of WS_2 powder, added in a dielectric medium on the metal removal rate and root mean square surface roughness has evaluated. The effect of cryogenically treated wire on the metal removal rate and root mean square surface roughness during machining has carried out. Taguchi method and genetic algorithm have used to optimize machining performance measures.

2 Experiments

The experiments were conducted on a wire EDM machine (model ELPULS-15) supplied by M/s Electronica, Pune, India, as shown in Fig. 1a. The two types of wire were

Fig. 1 **a** Experimental setup for WEDM used in this study. **b** Set up used for deep cryogenic treatment

selected as tool material: one zinc coated wire and another deep cryogenic treated zinc coated wire. The cryogenically treated wire has fine grains than untreated because there is a reduction of vacancies inside the lattice during treatment [25]. The EN-42 spring steel was selected as work-piece material. The chemical composition of this spring steel is given in Table 1. Figure 1b shows the set up used for deep cryogenic treatment.

Tungsten disulfide (WS_2) microparticles were selected for the powder mixed wire EDM process. The WS_2 microparticles are partially soluble in water and acidic solutions. They are widely used as solid lubricants in high-temperature environments. The WS_2 microparticles appear in the form of a blue-grey powder. The powder consists of Tungsten (74.13%) and Sulphur (25.87%) having a density of 7.5 g/cm^3 ; melting point 1250°C ; particle size $4\text{--}5 \mu\text{m}$.

The distilled water was used as a dielectric fluid, and its conductivity was measured to be 200 S/min . The WS_2 powder was added (concentration of 1 g/l) in the dielectric fluid. It was found that the conductivity of the dielectric was reduced to 10 S/min . The reduced conductivity of dielectric fluid eliminates the wire breakage problem at elevated on time. During machining, it was found that the MRR increases with the addition of WS_2 powder (1 g/l) in the dielectric as compared to the neat dielectric. The higher concentration of the WS_2 powder (2 g/l) does not produce any significant results on conductivity and MRR. Hence, it was decided to select the WS_2 powder 1 g/l for the entire experimental work. Table 2 shows the input parameter selection and the levels used in the experiments. The input parameters have been selected as per the literature available and also, the authors want to analyze these parameters effect, these input parameters are shown in Table 2.

Four working parameters namely: T_{on} , T_{off} , F_{wf} and, F_{sf} were selected, and their three levels were chosen. The experiments were performed according to MINITAB 17.

Table 1 Chemical composition of the workpiece (in wt%)

Fe	C	Mn	Si	P	S
97.9	0.75–0.90	0.60–0.90	0.35	0.05	0.05

Table 2 Input parameter selection and their levels

Input parameter	Levels		
	1	2	3
On Time, T_{on} (μs)	110	115	117
Off Time T_{off} (μs)	50	55	60
Wire Feed, F_{wf} (m/min)	4	5	6
Servo Feed F_{sf} (mm/min)	2200	2250	2300

Three sets of the L-9 array and two machining conditions were selected:

- (i) Zinc coated brass wire as an electrode and distilled water as a dielectric
- (ii) Cryogenic treated zinc-coated brass wire as electrode and tungsten sulfide powder in the dielectric.

2.1 Taguchi method

The Taguchi method is used to optimize the process parameters in the current study on the EDM machining process. The signal-to-noise (S/N) ratio is evaluated using the relative “quality” of a particular parameter design. The main objective of the present study is to identify the conditions of EDM machining to minimize root mean square

Similarly, to identify the EDM machining condition which maximizes the MRR, the higher-is-better S/N ratio is applicable as given by [26]

$$\frac{S}{N} = -10 \log \frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} b \quad (2)$$

Signal to noise ratios is calculated for MRR and root mean square surface roughness. The design of experiment tables is generated from MINITAB-17 for Taguchi analysis.

2.2 Genetic algorithm

The genetic algorithm is used to find the effect of operating parameters on the response of the machine. The basic working principle of the genetic algorithm is given below: In MATLAB first following functions are defined:

function Y = name (a)

---Use a name for function

*Y = a(1) * A - a(2) * B + a(3) * C - a(4) * D - E ;* ---Define objective function

End

surface roughness. For the said condition, the lower-is-better (LB) S/N ratio is applicable, which is given by [26]

$$\frac{S}{N} = -10 \log \frac{1}{n} \sum_{i=1}^n y_i^2 \quad (1)$$

Here (a) is a matrix for T_{on} , T_{off} , F_{wf} and F_{sf} which are denoted in the function as $a(1)$, $a(2)$, $a(3)$ and $a(4)$ respectively. A, B, C, D and E are coefficients of T_{on} , T_{off} , F_{wf} and F_{sf} constant term respectively. We will form four functions as genetic algorithm objective functions.

Now we define a function as ‘name’. We write the genetic algorithm optimization code as following in MATLAB:

ObjFcn = @name;

---Our defined function is objective function now.

nvars = 4;

---Define number of variables.

LB = [100 50 3 2200];

---Define lower bounds for variables.

UB = [120 60 8 2300];

---Define upper bounds for variables.

[a, fval] = ga(ObjFcn,nvars,[],[],[],[],LB,UB); ---genetic algorithm optimization command (Four

empty brackets are for inequalities and Constraint functions if there are any).

Table 3 S/N ratio for MRR and surface finish for zinc coated wire and dielectric (pure distilled water)

T_{on} (μ s)	T_{off} (μ s)	F_{wf} (m/min)	F_{sf} (mm/min)	MRR (mm ³ /min)	S/N MRR	Surface finish (μ m)	S/N surface finish
110	50	4	2200	3.237	10.202854	3.671	− 11.2956
110	55	5	2250	1.980	5.9333038	3.624	− 11.18376
110	60	6	2300	1.695	4.5859558	3.491	− 10.85899
115	50	5	2300	5.205	14.328414	3.927	− 11.88121
115	55	6	2200	3.253	10.245681	3.872	− 11.75870
115	60	4	2250	3.689	11.338173	3.576	− 11.06795
117	50	6	2250	5.280	14.452678	4.216	− 12.49801
117	55	4	2300	5.174	14.276528	4.013	− 12.06938
117	60	5	2200	4.631	13.313495	3.918	− 11.86128

Table 4 Response values for S/N ratios and means: larger is better (MRR)

Level	Response values for S/N ratios: Larger is better (MRR)				Response values for means: larger is better (MRR)			
	T_{on} (μ s)	T_{off} (μ s)	F_{wf} (m/min)	F_{sf} (mm/min)	T_{on} (μ s)	T_{off} (μ s)	F_{wf} (m/min)	F_{sf} (mm/min)
1	6.907	12.995	11.939	11.254	2.304	4.574	4.033	3.707
2	11.971	10.152	11.192	10.575	4.049	3.469	3.939	3.650
3	14.014	9.746	9.761	11.064	5.028	3.338	3.410	4.025
Delta	7.107	3.249	2.178	0.679	2.724	1.236	0.624	0.375
Rank	1	2	3	4	1	2	3	4

Table 5 S/N ratios for MRR and surface finish for cryogenically treated wire and WS₂ powder mixed in a dielectric

T_{on} (μ s)	T_{off} (μ s)	F_{wf} (m/min)	F_{sf} (mm/min)	MRR (mm ³ /min)	S/N MRR	Surface finish (μ m)	S/N surface finish
110	50	4	2200	3.638	11.2172539	3.418	− 10.675441
110	55	5	2250	3.330	10.4488847	3.514	− 10.916035
110	60	6	2300	2.222	6.93488109	3.243	− 10.218939
115	50	5	2300	4.872	13.7541456	3.875	− 11.765434
115	55	6	2200	3.552	11.0094591	3.739	− 11.455109
115	60	4	2250	3.056	9.703067	3.518	− 10.925917
117	50	6	2250	5.480	14.7756112	4.147	− 12.354681
117	55	4	2300	4.470	13.0061505	3.927	− 11.881218
117	60	5	2200	5.060	14.0833536	3.931	− 11.890061

3 Results and discussion

The S/N ratios for MRR and surface finish for zinc coated wire and distilled water as dielectric fluid was determined. The regression equations for MRR and surface finish without WS₂ powder and with zinc-coated wire are presented as Eqs. 3 and 4 respectively as given below:

$$MRR = -38.49 + 0.3814 \times T_{on} - 0.1236 \times T_{off} - 0.312 \times F_{wf} + 0.00318 \times F_{sf} \quad (3)$$

$$SR = -1.54 + 0.0599 \times T_{on} - 0.02763 \times T_{off} + 0.0532 \times F_{wf} - 0.0001 \times F_{sf} \quad (4)$$

Table 3 shows the S/N ratios for MRR and surface finish for zinc coated wire and dielectric (pure distilled water). The main effect plots for S/N ratios and means shows maximum variations for T_{on} . Hence it was the most significant parameter for maximum MRR. The MINITAB design of experiments analysis shows T_{on} has rank 1 followed by T_{off} , F_{wf} and F_{sf} .

Fig. 2 Main effect plot for **a** S/N ratio, **b** means: larger is better (MRR)

Fig. 3 Main effect plot for **a** S/N ratio, **b** means of MRR with cryogenically treated wire and WS_2 powder

Response Table 4 shows a variation which subjected to larger is better. For the selected values of $T_{on}=117 \mu s$; $T_{off}=50 \mu s$; $F_{wf}=4 \text{ m/min}$; $F_{sf}=2300 \text{ mm/min}$; the predicted value of MRR was found to be $6.279 \text{ mm}^3/\text{min}$.

The S/N ratios for MRR and surface finish for cryogenically treated wire and WS_2 powder mixed in dielectric were determined are shown in Table 5. Figure 2 shows the main effects plots for the S/N ratio and means. The regression equations for MRR and surface finish with WS_2 powder and with cryogenically treated wire are presented as Eqs. 5 and 6 respectively as given below:

$$MRR = -13.1 + 0.2532 \times T_{on} - 0.1217 \times T_{off} + 0.015 \times F_{wf} - 0.00229 \times F_{sf} \quad (5)$$

$$SR = -4.25 + 0.0827 \times T_{on} - 0.02493 \times T_{off} + 0.0443 \times F_{wf} - 0.000143 \times F_{sf} \quad (6)$$

Based on the response values for S/N ratios and the mean for MRR, it was decided to use the S/N ratio larger is better. The selected values are as followed: $T_{on}=117 \mu s$; $T_{off}=50 \mu s$; $F_{wf}=5 \text{ m/min}$; $F_{sf}=2200 \text{ mm/min}$; it was found that the maximum MRR was obtained at lower servo feed and higher wire feed. The predicted value of $MRR=6.37947 \text{ mm}^3/\text{min}$ (Fig. 3).

Main effect plots for S/N ratios and means are shown in Fig. 4. The variation in T_{on} was obtained maximum as compared to other input parameters. Hence it is the most

Fig. 4 Main effect plot for **a** S/N ratio, **b** means of surface finish with cryogenically treated wire and WS_2 powder

Table 6 Response values for S/N ratios and means: smaller is better (surface finish)

Level	Response values for S/N Ratios: Smaller is better (surface finish)				Response values for means: Smaller is better (surface finish)			
	T_{on} (μs)	T_{off} (μs)	F_{wf} (m/min)	F_{sf} (mm/min)	T_{on} (μs)	T_{off} (μs)	F_{wf} (m/min)	F_{sf} (mm/min)
1	-10.60	-11.60	-11.16	-11.34	3.392	3.813	3.621	3.696
2	-11.38	-11.42	-11.52	-11.40	3.711	3.727	3.773	3.726
3	-12.04	-11.01	-11.34	-11.29	4.002	3.564	3.710	3.682
Delta	1.44	0.59	0.36	0.11	0.610	0.249	0.152	0.045
Rank	1	2	3	4	1	2	3	4

significant parameter for minimum surface finish having rank 1. MINITAB shows surface finish increases rapidly with T_{off} . As we increase T_{on} surface finish decreases. The F_{sf} has a minimum effect on root mean square surface roughness.

Table 6 shows response value for S/N ratio and means for root mean square surface roughness (smaller is better). It was found that the level 1 of T_{on} , level 3 of T_{off} , level 1 of F_{wf} , level 3 of F_{sf} . The selected values are as followed: $T_{on} = 110 \mu s$; $T_{off} = 60 \mu s$; $F_{wf} = 4 \text{ m/min}$; $F_{sf} = 2300 \text{ mm/min}$; it was found that the optimum value of surface finish was achieved for the higher value of servo feed and the predicted value of surface finish was to be $3.15433 \mu m$.

Figure 4 shows the main effects plots for the S/N ratio and means. The regression equation for the surface finish with WS_2 powder and with cryogenically treated wire is presented in Eq. 6.

3.1 Genetic algorithm

The genetic algorithm method was used to achieve an optimal solution. The cross over probability (P_c), mutation probability (P_m) and the number of generations of particular generation has been varied. The number of feasible solutions was obtained as followed: Population size: 20;

Total no. of generations: 100; Cross over probability (P_c): 0.80; Mutation probability (P_m): 0.01; Migration probability (P_{mg}): 0.20

The genetic algorithm is used to optimize surface finish and MRR. The Eqs. (3) and (5) are maximized for MRR. Similarly, Eqs. (4) and (6) are minimized for surface finish using MATLAB genetic algorithm optimization tool. Optimum Parameters and predicted Value using the genetic algorithm on MATLAB is presented in Table 7. The variables of the objective functions are limited by its upper and lower bounds and are given as:

$$100 \leq \text{on time} \leq 120;$$

$$50 \leq \text{off time} \leq 60;$$

$$3 \leq \text{wire feed} \leq 8;$$

$$2200 \leq \text{servo feed} \leq 2300$$

Table 7 Optimum parameters and predicted value using the genetic algorithm on MATLAB

Conditions	Response	T_{on} (μ s)	T_{off} (μ s)	F_{wf} (m/min)	F_{sf} (mm/min)	Predicted value
Zinc coated brass wire and distilled water	MRR (m^3/min)	120	50	3	2280	7.4122
	Surface finish (μ m)	100	60	3	2290	2.7236
Cryogenically treated wire and WS_2 powder in the dielectric	MRR(m^3/min)	120	50	8	2200	6.2735
	Surface finish(μ m)	100	58	3	2290	2.3570

3.1.1 Objective functions with constraints for MRR and surface finish with zinc coated wire and distilled water as dielectric

The formulated single-single objective optimization functions are formed by regression analysis as given in Eqs. (3) and (4) for MRR and SR. Our purpose is to maximize MRR and minimize surface roughness.

Maximize:

$$MRR = -38.49 + 0.3814 \times T_{on} - 0.1236 \times T_{off} + 0.312 \times F_{wf} - 0.00318 \times F_{sf}$$

Minimize:

$$SR = -1.54 + 0.0599 \times T_{on} - 0.02763 \times T_{off} + 0.0532 \times F_{wf} - 0.000100 \times F_{sf}$$

The variables of the function are limited by its upper and lower bounds as given below:

$$100 \leq T_{on} \leq 120;$$

$$50 \leq T_{off} \leq 60;$$

$$3 \leq F_{wf} \leq 8;$$

$$2200 \leq F_{sf} \leq 2300.$$

3.1.2 Objective functions with constraints for MRR and surface finish with cryogenically treated wire and WS_2 powder in the dielectric

The single-single objective optimization functions are formed by regression analysis as given in Eqs. (5) and (6) for MRR and SR. Our purpose is to maximize MRR and minimize surface roughness.

Maximize:

$$MRR = -13.1 + 0.2532 \times T_{on} - 0.1217 \times T_{off} + 0.015 \times F_{wf} - 0.00229 \times F_{sf}$$

Minimize:

$$SR = -4.25 + 0.0825 \times T_{on} - 0.02493 \times T_{off} + 0.0443 \times F_{wf} - 0.000143 \times F_{sf}$$

The variables of the function are limited by its upper and lower bounds and are given as

$$100 \leq T_{on} \leq 120;$$

$$50 \leq T_{off} \leq 60;$$

$$3 \leq F_{wf} \leq 8;$$

$$2200 \leq F_{sf} \leq 2300.$$

3.2 Contour plots

It was observed that the T_{on} and T_{off} are key parameters that affect MRR and surface finish. Now with the help of contour plots using MINITAB. The estimation regarding the MRR and surface finish depending on T_{on} and T_{off} was evaluated in the form of contour plots for MRR and surface finish using two types of dielectric fluids namely: zinc coated wire with distilled water as dielectric and cryogenically treated wire with WS_2 powder in distilled water as the dielectric. The plots for MMR and surface finish for zinc coated wire and distilled water as dielectric and cryogenically treated wire and WS_2 powder in the dielectric are shown in Figs. 5 and 6 respectively.

Tables 8 and 9 show the response parameters (MRR and surface finish) predicted and experimental values for various operating conditions. The percentage error in the MRR value are almost similar (~6.5%), and error in surface finish was on the higher side (~8.5%) for zinc-coated brass wire and WS_2 Powder in dielectric and zinc-coated brass Wire and distilled water as compared to cryogenically treated zinc-coated brass wire and WS_2 powder in dielectric (~6.8%). Now, the results predicted from the Taguchi method and genetic algorithm are in good agreement. However, the genetic algorithm shows better and accurate results. The genetic algorithm has an advantage over the Taguchi method because we can vary the constraints to find more accurate results in a wide range.

Fig. 5 Contour plot for MRR and surface finish with zinc coated wire and distilled water as dielectric

Fig. 6 Contour plot for the surface finish with cryogenically treated wire and WS_2 powder in the dielectric

Table 8 Results obtained by using the Taguchi method

Conditions	Response	T_{on} (μs)	T_{off} (μs)	F_{wf} (m/min)	F_{sf} (mm/min)	Predicted value	Experimental value	Error (%)
Zinc coated brass wire and distilled water	MRR (m^3/min)	117	50	4	2300	6.279	5.876	6.4
	Surface finish (μm)	100	60	4	2250	3.3796	3.675	8.7
Cryogenically treated zinc-coated brass wire and WS_2 powder in the dielectric	MRR (m^3/min)	117	50	5	2200	6.3794	5.9435	6.7
	Surface finish (μm)	110	60	4	2300	3.1543	3.3714	6.8

Table 9 Results obtained by using the genetic algorithm

Conditions	Response	T_{on} (μs)	T_{off} (μs)	F_{wf} (m/min)	F_{sf} (mm/min)	Predicted value	Experimental value	Error (%)
Zinc coated brass wire and distilled water	MRR (m^3/min)	120	50	3	2280	7.4122	7.105	4.10
	Surface finish (μm)	100	60	3	2290	2.7236	2.817	3.40
Cryogenically treated zinc-coated brass wire and WS_2 powder in the dielectric	MRR (m^3/min)	120	50	8	2200	6.2735	6.1932	1.20
	Surface finish (μm)	100	58	3	2290	2.357	2.419	2.60

4 Conclusions

The study on process parameters optimization in WEDM on EN-42 spring steel by the Taguchi method and a genetic algorithm was carried out. From the investigation, the following conclusions were drawn:

- From the analysis of results, it was observed that cryogenic treatment had made a significant contribution to improving surface finish. The crystal's homogeneity due to the reduction of vacancies inside crystal lattice is the reason for this improvement. Cryogenic treatment of the wire significantly improved the surface finish of the machined surface.
- For EN-42 material, root mean square surface roughness and is affected by pulse on time (on time). Increasing the pulse on time sustains spark for a longer period so more thermal energy is generated. Resulting craters will be broader and deeper; therefore, the surface finish will be rougher.
- When the cryogenically treated zinc-coated brass wire was used along with WS_2 powder in dielectric fluid, the MRR was increased, because the electrical conductivity of wire increased, and a significant improvement was also observed in root mean square surface roughness.
- Mixing WS_2 powder in the dielectric fluid results in a decrease in the conductivity of the dielectric. The low conductivity of dielectric fluid facilitates operating the machine at higher T_{on} , and the wire breakage problem was eliminated.
- MRR increases with the increase in T_{on} and decrease in T_{off} . Further, the increase in T_{on} results in broader and deeper craters. Therefore, the surface becomes rough.
- With the increase in the T_{on} , the higher value of MRR and significant improvement in the surface finish were observed for cryogenically treated zinc-coated brass wire along with the WS_2 powder in the dielectric fluid. Therefore, for better MRR and good surface finish, the parameters should be set at lower levels of F_{wf} and F_{sf} in combination with higher values of T_{on} .
- In Taguchi analysis we find out that rank of parameters is always in order (1) on time, (2) off time, (3) wire feed, (4) servo feed. But in the case of zinc-coated brass wire and WS_2 powder in dielectric off time becomes the most significant parameter, while wire feed has its lowest significance.
- A higher MRR is obtained at high on time and lower off time. The Taguchi method suggests a maximum MRR of $5.9435 \text{ mm}^3/\text{min}$ which is obtained at the parameter combination of [117-50-5-2200]. According to the genetic algorithm the parameter combination is [120-50-3-2280] which yields $7.105 \text{ mm}^3/\text{min}$ value of MRR.

- A lower SR is obtained at parameter combination [110-60-4-2300] according to the Taguchi method. Result obtained is $3.3714 \mu\text{m}$. The genetic algorithm suggests the parameters combination of [100-58-3-2290], which gives the lowest SR of $2.419 \mu\text{m}$.

Funding This study was funded by the Mechanical Engineering Department of the G. B. Pant Engineering College, Pauri Garhwal, Uttarakhand-246194, India.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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