A STUDY OF COPPER AND ZINC CONTAMINATION ON THE WORK PIECE SURFACE BASED ON WEDM

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Abstract: In this work is presented an investigation on Wire Electric Discharge Machining (WEDM) of Pure Titanium (Grade-2). Pure Titanium and its alloys are the most suitable metallic materials for biomedical applications. In health care, they are used for implant devices like knee and hip implants, fixing materials for bones like nails and screws, and in the oral and maxillofacial surgery. Properties like good biocompatibility, high corrosion resistance, and high fracture strength make titanium parts the perfect solution for bio-implants. The more frequent use of the titanium necessitates an economical machining process. Conventional processes like milling, grinding or drilling have their limits because of the material's mechanical properties which cause high tool wear. WEDM proves to be an alternative especially for manufacturing complex parts as there is no actual contact with tool and the work piece. Within this study, the capabilities of Wire-EDM for the manufacturing of clean surfaces with distinct Surface Roughness (SR) and Machining Speed (MS) are conducted through optimization of process parameters. Taguchi technique is used for optimization and the experiments are conducted according to Taguchi Design of Experiments (DOE). Different wire electrode materials have been used considering a possible copper and zinc contamination on the work piece surface.

Keywords: WEDM, Titanium Grade 2, Taguchi Design, Optimization.

1. Introduction

Increased use of titanium and its alloys as biomaterials stems from their lower modulus, superior biocompatibility, and better corrosion resistance when compared to more conventional stainless and cobalt-based alloys. As a hard tissue replacement, the low elastic modulus of titanium and its alloys is generally viewed as a biomechanical advantage because the less elastic modulus can result in lower stress shielding. Hence, for the present research pure Titanium has been chosen as the test material.

Titanium and its alloys are often used in the medical sector. It is used for joint substitutions like knee and hip implants, fixing materials for bones like nails and screws, and in the oral and maxillofacial surgery because of the materials' characteristics like good biocompatibility and bio adhesion in addition to corrosion resistance and specific mechanical properties. However, problems arise during manufacturing of titanium implants with conventional processes like milling, grinding or drilling obtain their limits because of the materials mechanical properties which cause e.g. high tool wear.

Electro Discharge Machining (EDM) represents an alternative especially for manufacturing of filigree parts. Furthermore, it is applicable for flexible manufacturing process that allows to machine implants which can be adapted to specific patients' demands. In terms of a single-unit production, it is hereby an economic process. Further differences between EDM and conventional manufacturing processes can be pointed out in terms of surface integrity. Through machining by cutting processes smearing and plastic deformation (e.g. micro ploughing) might lead to small cavities. These negative surface conditions do not occur after machining by EDM because of a nearly force free process. This leads to a surface which can be very well sterilised. Especially the Wire-EDM process leaves residues like copper and zinc on surfaces. These residues substantially affect the biocompatibility. One way to decrease or eliminate this problem is to use non-common wire electrodes. These are electrodes made of materials which themselves feature a high biocompatibility.

Another option could be to use Trilayered wires but these are very expensive to produce or even non-producible. Fig. 1 shows the schematic diagram of the Wire Electric Discharge Machining (WEDM) process.

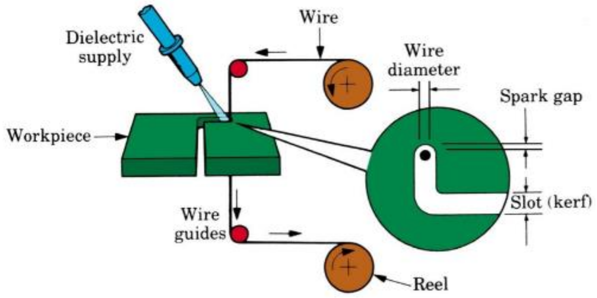


Figure 1: Wire EDM process diagram Tsai et al., (2003)

This paper focuses on a basic study on the capabilities of Wire-EDM for the manufacturing of clean surfaces with distinct roughness and a high surface integrity. Common wire materials will be analysed regarding a possible copper and zinc contamination of the work piece surface due to re-solidification of small particles originating from the wire. Furthermore, the process itself will be optimised by parametric optimization of various process parameters to obtain distinct surface roughness and better machining speed of WEDM.

2. Literature Review

Electric Discharge Machining amongst the many non-conventional machining methods has numerous applications in the current industrial processes.

The EDM process converts the electrical energy generated in a channel between a cathode and an anode to thermal energy which creates sufficient high temperature for the erosion of work piece material [7].

This distinct feature of thermo-electric conversion of EDM makes it suitable for manufacturing of complex parts particularly for aerospace and automotive industry, and surgical instruments [3]. In EDM process, the desired shape of the object is obtained by electrical discharges i.e., sparks. A localised spark is produced between the work-piece and the electrode in the presence of a dielectric fluid. Here, generally deionized water acts as a dielectric fluid which filters and directs the sparks. The water also acts as a coolant and also helps in flushing away the residual metal particles [6]. In Wire EDM, a moving metallic wire is used as the electrode to cut a programmed contour. The wire movement is controlled numerically which provides accuracy for machining of complex two and three dimensional work piece configurations. Wire EDM is a non-contact type machining method which provides an economical and efficient way for cutting Metal Matrix Composite materials. The work material Hardness does not possess any disadvantage in cutting as there is no relative contact between the wire and the work material [4]. Instead of cutting the material, the WEDM produces high temperature which melts or vaporizes the material, leaving very little debris providing accurate results. A taut thin wire discharges the electrified current which acts as a cathode guided alongside the desired cutting path. The work piece undergoing machining is usually fixed on a table. High accuracy instrumentation comprising of CNC systems is used to control the movements of work piece which reduces the positioning errors to a large extent [2].

Some of the common wire electrode is made up of copper because of its higher electrical conductivity but it wears rapidly and its tension ability is poor [1].

From literature, it has been found that many researchers have focused on the developments of EDM, WEDM, and micro-WEDM. Hence, in this study, an attempt has been made to determine the effect of process parameters and wire material on the responses like MRR and surface roughness. Taguchi's orthogonal array has been used for conducting the experiments and presented the results of wire materials influence on performance of WEDM process for Titanium grade 2.

3. Experiments and Data Collection

Experiments were conducted by varying the process parameters such as Pulse ON Time (T ON), Pulse OFF Time (T OFF), Current (IP), Wire Feed Rate (WF) on an EZEECUT NXG CNC WEDM machine is shown in Fig. 2.

The MAHR Surface Roughness Tester shown in the Fig. 3 is used to calculate surface roughness values and R avg has been used for all the experimental plots and significant results have been obtained.

Figure 2: EXEECUT NXG CNC WEDM Machine

Figure 3: MAHR Surface Roughness Tester

Design of experiments

Design of experiments (DOE) or experimental design is the design of any information gathering exercises where variation is present, whether under the full control of the experimenter or not. Classical experimental design often requires a large number of experiments to be carried out when number of machining parameters increase.

Genichi Taguchi developed this statistical method for improving the quality of the products and manufacturing goods which finds many applications in the field of engineering [5]. This method provides an efficient, systematic and simplistic approach for optimization of the design for better performance, higher quality and cost cutting. This method is more effective when used with the discrete and qualitative design parameters.

The optimization process in a Taguchi method is carried out in 3 steps: System design, parameter design, and tolerance design. The main thrust of this method lies in the usage of a method for product and process design i.e. Parameter design, which focuses on deciding the parameters for developing the best of quality characteristics with minimal variations.

The S/N ratio is used to measure the quality characteristics deviating from the desired values.

The analysis includes 3 categories of quality characteristics: (i) Lower-the-better, (ii) Higher-the-better, and (iii) Nominal-the-better. The greatest S/N ratio value should be selected for best quality characteristics. In this study, 4 machining parameters were used as control factors and each parameter was designed to have 3 levels. According to the Taguchi quality design concept, a L9 orthogonal arrays table with 9 rows (corresponding to the number of experiments) was chosen for the experiments. Table 1 shows the distribution of levels of different parameters in a Taguchi Orthogonal Array.

In Table 2 and Table 3 the properties of the wires and process parameters of the WEDM is shown. The analysis using Taguchi is portrayed in Table 4.

Table 1. Taguchi's L9 Orthogonal Array

Exp. No.	T ON	T OFF	IP	Wire Feed
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 2. Properties of different types of wire used

	Material	Coating	Tensile	Elongation	Conductivity	Diameter
Coated wire	Cu Zn 36	Zn	900 N/mm2	1.50%	22% IACS	0.25 mm
Annealed Wire	Cu Zn 37	Zn	900 N/mm2	2%	22% IACS	0.25 mm

Table 3. Process parameters for WEDM and their considered levels

Symbol	**Control factor**	**Unit**	**Level 1**	**Level 2**	**Level 3**
A	Pulse ON Time (T ON)	µs	50	70	90
B	Pulse OFF Time (T OFF)	µs	4	6	9
C	Current (IP)	A	3	4	5
D	Wire Feed	mm/min	50	70	90

Table 4. Experimental Readings of SR, MS and S/N Ratio values for Machining Speed and SR

Wire	Ex. No	T ON	T OFF	IP	Wire. Feed	MS (mm/ min)	SR (µm)	S/N Ratio MS	S/N Ratio SR
Coated Wire	1	1	1	1	1	1.24	11	1.868433703	-20.8278537
	2	1	2	2	2	1.18	8.511	1.437640146	-8.59961181
	3	1	3	3	3	0.27	9.2376	-11.37272472	-9.31118306
	4	2	1	2	3	0.5	10.0069	-6.020599913	-20.0059912
	5	2	2	3	1	0.498	8.895	-6.055413145	-8.98291905
	6	2	3	1	2	0.59	10.659	-4.582959767	-0.55432924
	7	3	1	3	2	0.85	7.5138	-1.411621486	-7.51719262
	8	3	2	1	3	0.78	8.3414	-2.158107946	-8.42477895
	9	3	3	2	1	0.28	7.3834	-11.05683937	-7.36512794
Annealed Wire	10	1	1	1	1	1.112	11.5695	0.922095745	-1.26629181
	11	1	2	2	2	1.37	9.2105	2.734411343	-9.28566414
	12	1	3	3	3	0.608	11.3269	-4.321928415	-1.08222133
	13	2	1	2	3	0.392	8.5086	-8.13427866	-8.59716215
	14	2	2	3	1	0.18	9.176	-14.8945499	-19.2530681
	15	2	3	1	2	0.57	8.6392	-4.882502887	-8.72947056
	16	3	1	3	2	0.82	8.2458	-1.723722952	-8.32465594
	17	3	2	1	3	0.435	7.8961	-7.230214861	-17.9482528
	18	3	3	2	1	0.16	8.4904	-15.91760035	-8.57856302

4. Method of Analysis

Single Objective Optimization

Single response optimization is carried out to investigate the effects of machining parameters on Machining Speed (MS) and Surface Roughness (SR). According to the Taguchi method, S/N ratios in Eq. 1and 2 were calculated for each experiment. The objective of optimization is to maximize the MS and minimize the SR.

The response table for S/N ratios of MS is calculated considering the fact that MS is a larger-the-better performance characteristic; the maximization of the quality characteristic of interest is sought and is expressed as:

$$S / NRatio = -10 \log \left(\frac{1}{n} \right) \sum_{i=1}^{n} \frac{1}{y^2} \quad (1)$$

yij = observed response value i=1, 2... ....n; j = 1, 2...k ,n = number of replications

The surface roughness is the lesser-the-better performance characteristic and the S/N ratio for SR is calculated by:

$$S / NRatio = -10 \log \left(\frac{1}{n} \right) \sum_{i=1}^{n} y^2{}_{ij} \quad (2)$$

SEM and EDX Analysis for Coated and Annealed Wire

SEM and EDX analysis are performed on the samples obtained from single objective optimization of Surface Roughness of both Coated and Annealed wire. The objective of the analysis is to check the contamination levels of copper and other materials in the sample after wire electric discharge machining.

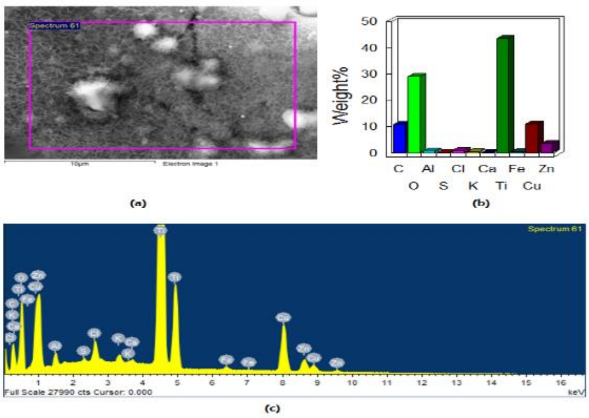


Figure 4: (a) SEM micrograph for spectrum 1, (b) Composition graph for spectrum 1, (c) EDX analysis for spectrum 1 for coated wire

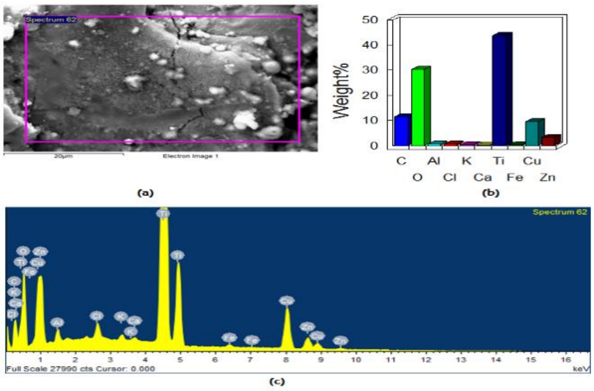


Figure 5: (a) SEM micrograph for spectrum 2, (b) Composition graph for spectrum 2, (c) EDX analysis for spectrum 2 for coated wire

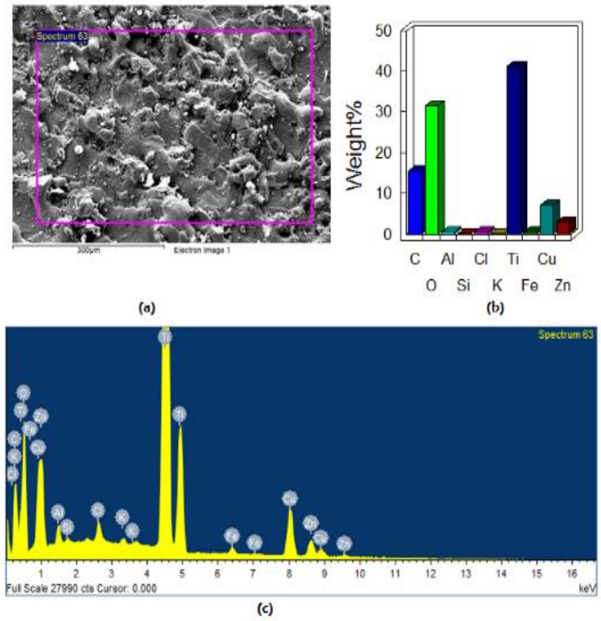


Figure 6: (a) SEM micrograph for spectrum 3, (b) Composition graph for spectrum 3, (c) EDX analysis for spectrum 3

Fig. 4, Fig. 5 and Fig. 6 shows the SEM results and composition of different materials that are present on the surface of the machined surface which are cut through coated wire for three spectrums shown in Table 5 respectively. According to SEM images of sample of coated wire, the fibrous network is having maximum Cu content as 11.0 % shown in Fig. 4. In the globular phases, the Cu content is reduced to 9.58% shown in Fig. 5.

Table 5. Experimental Readings of SR, MS and S/N Ratio values for Machining Speed and SR

	Spectrum 1		Spectrum 2		Spectrum 3	
Element	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)
C	10.7	22.84	11.51	23.9	15.51	29.84
O	28.99	46.43	30.25	47.14	31.56	45.59
Al	0.54	0.51	0.51	0.47	0.46	0.39
Si	0	0	0	0	0.09	0.08
S	0.12	0.09	0	0	0	0
Cl	0.77	0.56	0.58	0.4	0.45	0.3
K	0.31	0.21	0.22	0.14	0.15	0.09
Ca	0.12	0.08	0.13	0.08	0	0
Ti	43.6	23.32	43.68	22.73	41.16	19.86
Fe	0.32	0.15	0.3	0.13	0.49	0.2
Cu	11	4.44	9.58	3.76	7.09	2.58
Zn	3.53	1.38	3.24	1.24	3.05	1.08

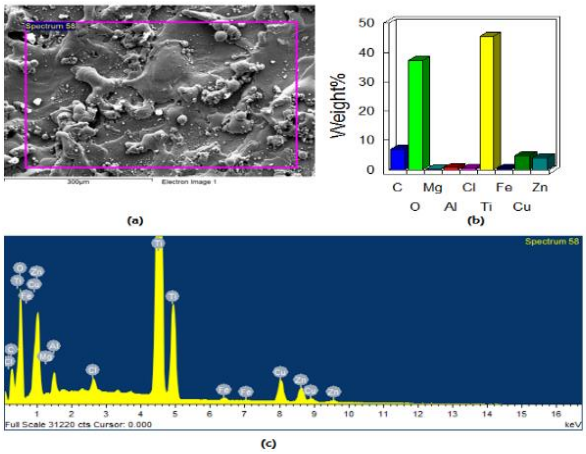


Figure 7: (a) SEM micrograph for spectrum 1, (b) Composition graph for spectrum 1, (c) EDX analysis for spectrum 1 for annealed wire

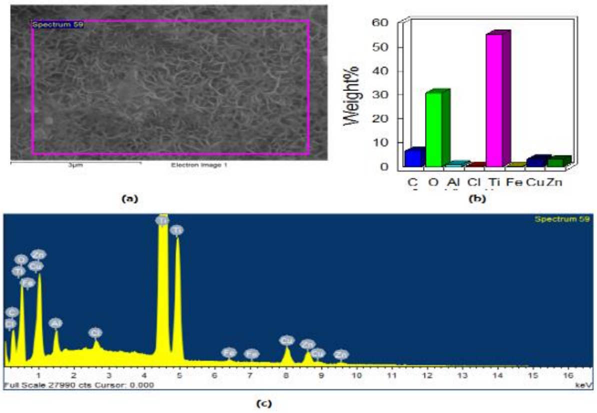


Figure 8: (a) SEM micrograph for spectrum 2, (b) Composition graph for spectrum 2, (c) EDX analysis for spectrum 2 for annealed wire

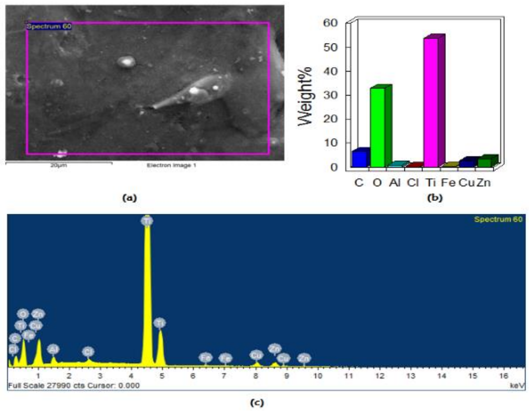


Figure 9: (a) SEM micrograph for spectrum 3, (b) Composition graph for spectrum 3, (c) EDX analysis for spectrum 3 for annealed wire

Fig. 7, Fig. 8, Fig. 9 shows the SEM results and composition of different materials that are present on the surface of the machined surface which are cut through annealed wire for three spectrums shown in Table 6 respectively. According to SEM images of sample of annealed wire, we can see that in Fig. 7, the surface appears as beach sand shaped with globular phases over it. There are some cracks visible to across the whole surface. At various points, EDAX analysis were performed. In the globular phases, more amount of Cu (4.72%) is seen. In the remaining matrix, the Cu content is reduced, which tells that there has been micro-segregation of Cu, with Cu accumulating in the globular phases. In the matrix dense fibrous network of the alloy is seen Fig. 8. Here the Cu content is reduced (3.11%). Some Cu less phases are also seen Fig. 9.

Table 6. Chemical Composition of sample for all spectrums

	Spectrum 1		Spectrum 2		Spectrum 3	
Element	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)
C	6.83	14.08	6.49	14.07	6.47	14.32
O	37.36	57.81	32.81	53.39	30.93	51.41
Mg	0.08	0.08	0	0	0	0
Al	0.76	0.7	0.77	0.74	0.79	0.77
Cl	0.44	0.3	0.33	0.24	0.29	0.21
Ti	45.56	23.55	53.64	29.15	55.24	30.67
Fe	0.3	0.13	0.15	0.07	0.18	0.09
Cu	4.72	1.84	2.51	1.03	3.11	1.3
Zn	3.96	1.5	3.3	1.32	3.01	1.22

5. Results and Discussion

Response time for the three levels of two different materials of annealed and non-annealed i.e. MS and SR is shown in Fig. 7(a) and (b) as well as in Fig. 8(a) and (b) respectively. Fig. 10 (a) indicates the optimal parameters for MS for coated wire, i.e. A1B1C1D2 and Figure 10 (b) indicates the optimal parameters for SR for Coated wire i.e. A3B2C3D2. The experimental results were carried out for the optimal parameters and the machining speed 1.23 mm/min and Surface Roughness 7.3626 µm were obtained in Table 9. Based on the ANOVA results for machining speed for coated wire Table 10 (a). The percentage contribution of Pulse OFF Time on the output MS is highest with 42.702 % followed by Pulse ON Time. Table 10 (b) shows that the most significant factor affecting the performance characteristic of SR is Pulse ON Time, which is followed by current, and Pulse OFF Time. Wire Feed rate has negligible effect on SR while using coated wire.

Fig. 10 (a) indicates the optimal parameters for MS for annealed wire, i.e. A1B1C1D2 and Fig. 10 (b) indicates the optimal parameters for SR for Annealed wire i.e. A3B2C2D2.The experimental results were carried out for the optimal parameters and the machining speed 1.39 mm/min and Surface Roughness 7.823µm were obtained in Table 9. Based on the ANOVA results for machining speed for coated wire in Table 11 (a). The percentage contribution of Pulse ON Time on the output MS is highest with 55.424 % followed by Wire Feed rate. Table 11 (b) shows that the most significant factor affecting the performance characteristic of SR is Pulse ON Time, which is followed by Wire Feed rate, Current, and Pulse OFF Time.

Table 7. (a): Response Table for S/N Ratios for MS
(b): Response Table for S/N Ratios for SR

Level	T ON	T OFF	IP	Wire Feed
1	-2.689	-1.855	-1.624	-5.081
2	-5.553	-2.259	-5.213	-1.519
3	-4.876	-9.004	-6.28	-6.517

Level	T ON	T OFF	IP	Wire Feed
1	-19.58	-19.45	-19.94	-19.06
2	-19.85	-18.67	-18.66	-18.89
3	-17.77	-19.08	-18.6	-19.25

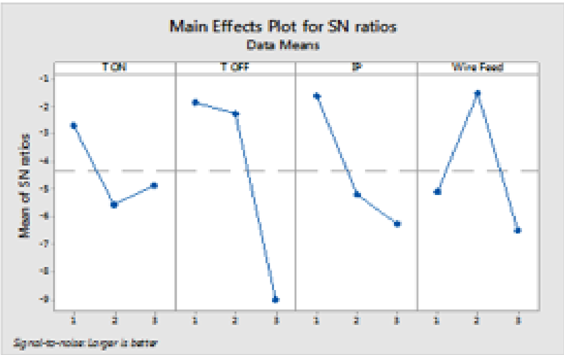


Figure 10: (a): Mean of S/N ratio for Machining Speed for Coated Wire

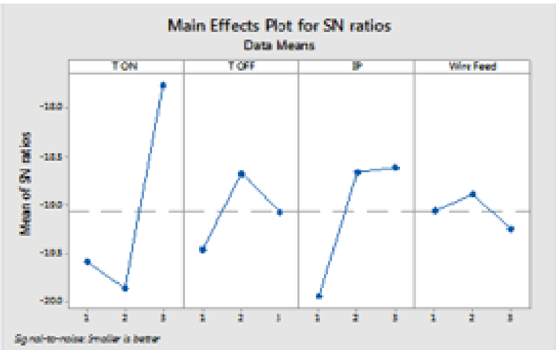


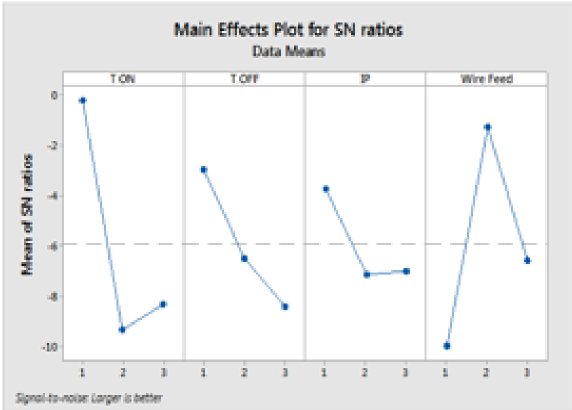
Figure 110: (b): Mean of S/N ratio for SR for Coated Wire

Table 8. (a): Response Table for S/N Ratios for MS

Level	T ON	T OFF	IP	Wire Feed
1	-0.2218	-2.9786	-3.7302	-9.9634
2	-9.3038	-6.4635	-7.1058	-1.2906
3	-8.2905	-8.374	-6.9801	-6.5621

Table 8. (b): Response Table for S/N Ratios for SR

Level	T ON	T OFF	IP	Wire Feed
1	-20.54	-19.4	-19.31	-19.7
2	-18.86	-18.83	-18.82	-18.78
3	-18.28	-19.46	-19.55	-19.21



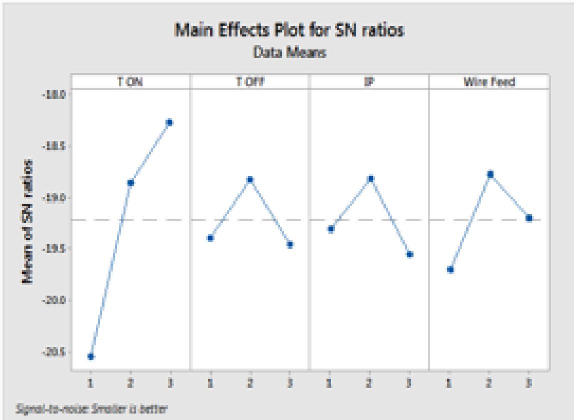


Figure 11: (a): Mean of S/N ratio for Machining Speed for Annealed Wire, (b): Mean of S/N ratio for SR for Annealed Wire

Table 9. Single Response Optimization Results for Coated and Annealed Wire

	Response Characteristic	Optimal Condition	Exp. Results
Coated wire	Machining Speed (mm/min)	A1B1C1D2	1.23
	Surface Roughness (µm)	A3B2C3D2	7.3626
Annealed Wire	Machining Speed (mm/min)	A1B1C1D2	1.39
	Surface Roughness (µm)	A3B2C2D2	7.823

Table 10. (a): ANOVA Results for MS (Coated Wire)

Source	DF	SS	MSS	% Contribution
T ON	2	0.2141	0.10703	21.33107502
T OFF	2	0.4286	0.21428	42.70200259
IP	2	0.1693	0.08464	16.86758992
WF	2	0.1918	0.09591	19.10929561
Error	0			
Total	8	1.0037		

Table 10. (b): ANOVA Results for SR (Coated Wire)

Source	DF	SS	MSS	% Contribution
T ON	2	7.8879	3.94397	59.3284845
T OFF	2	1.2866	0.6433	9.677103939
IP	2	3.9805	1.99027	29.93915143
WF	2	0.1402	0.0701	1.054507984
Error	0			
Total	8	13.2953		

Table 11. (a): ANOVA Results for MS (Annealed Wire)

Source	DF	SS	MSS	% Contribution
T ON	2	0.74165	0.37083	55.42477506
T OFF	2	0.1673	0.08365	12.50261561
IP	2	0.04397	0.02198	3.285953427
WF	2	0.3852	0.1926	28.78665591
Error	0			
Total	8	1.33812		

Table 11. (b): ANOVA Results for SR (Annealed Wire)

Source	DF	SS	MSS	%Contribution
T ON	2	10.2417	5.1208	72.95697393
T OFF	2	0.99	0.495	7.052286651
IP	2	1.1616	0.5808	8.274683003
WF	2	1.6447	0.8223	11.71605642
Error	0			
Total	8	14.038		

6. Conclusions

The present work focuses on optimization of parameters of wire electric discharge machining and their effects of different wires to improve the surface quality (reduce contamination), surface characteristics (distinct surface roughness), and time of operation (higher machining speed). The material used in this study is pure Titanium (Grade 2) owing to its better biocompatibility. Various parameters affecting the machining conditions are considered for single and multi-response optimization. The conclusions obtained are as follows. From single response optimization, it is observed that machining through annealed wire provides higher machining speed. However, it also results in higher surface roughness. The SEM and EDAX results show that the contamination levels in annealed wire, especially of copper, is significantly lower than the Zinc coated wire. This is due to better diffusion of zinc and copper in the annealed wire which avoids spark erosion from the wire to the material. Overall, it is recommended to use annealed wire during Wire Electric Discharge Machining for biological applications as it provides better results in terms of both machining speed and biocompatibility.

Future work can be performed by studying effects of other types of wire like molybdenum wire, brass wire and composite wires for obtaining better results. Different biocompatible materials like titanium alloys, stainless steel, magnesium alloys can also can be studied in terms of better machinability and surface characteristics.

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