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Optimizing the Surface Parameters of Titanium (Ti-6Al-4V) Alloy Specimens using WEDM Process based on Taguchi-DEAR Algorithm

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ABSTRACT

Because of its excellent mechanical qualities and weldability, titanium alloy is used in many different biomedical applications. Wire electrical discharge machining may be used to machine materials with such greater strengths and intricate forms. Using Taguchi-data envelopment analysis-based ranking (DEAR) approach and zinc-diffused coated brass wire electrode to improve Titanium alloy machining was the goal of this research project. The quality metrics that were taken into consideration were surface roughness, kerf width, and material removal rate. Among the selected factors, with an error of 2.7%, the optimal configuration of input factors was determined to be 130 µs (T_{on}), 40 µs (T_{off}), 50 V (SV), 6 A (IP), and 8 kg (WT). Due to its relevance in the process of deionization, the T_{on} is the highest influential parameter for creating quality measurements.

Keywords: titanium alloy, DEAR, MCDM, WEDM.

INTRODUCTION

Titanium (alpha-beta) alloy (Ti-6Al-4V) is used in the synthesis of dental specimens because of the exceptional physical features it has, including a stronger resistance to corrosion and substantial strength [1]. Titanium alloy must have a sufficient surface quality and be free from any residual stress in order to be used as a material for dental implants. It is particularly difficult to remove using conventional machining procedures because of the material's great strength. Because of this, non-traditional methods of material removal are employed, including abrasive-water jet machining (AWJM), wire electrical discharge machining (WEDM), hybrid machining, laser beam machining (LBM), and electro chemical machining (ECM). The machining technique produces an exceptional surface polish that is required for titanium alloy when it is utilized as a dental material. Because of the vibrations that occur when using the standard way of machining, the end product has a greater level of residual stress [2]. On the machined specimens, both LBM and hybrid cutting techniques leave behind a heat affected zone (HZ) that is rather large [3]. Making a fault in the laser power selection can have a detrimental effect on the LBM process's ability to machine titanium alloy [4]. The AWJM technique results in a significant reduction in the thickness of the specimens of titanium alloy [5]. Corrosion of the workpiece specimen is a possibility that may arise from the ECM process [6]. In order to make effective use of titanium alloy as a biomaterial, the specimen in question has to have an excellent level of surface polish and functionality throughout the machining process [7]. To achieve optimal performance measurements, the quality standards of machined specimens must meet the highest possible criteria. The WEDM technique is commonly employed in the fabrication of titanium components due to its capability to significantly minimize taper and kerf widths. The nonlinear characteristics of the WEDM process necessitate the optimization of process parameters to attain more precise performance metrics. During the EDM process, complex phenomena such as high-temperature plasma formation and rapid thermal cycles occur [8]. The intense heat generated can cause localized melting and vaporization, leading to the formation of a recast layer [9, 10]. The formation of a white layer, a byproduct of these high-temperature and plasma-induced phenomena, can serve as an effective mechanism for controlling surface quality. The enhancement of the input process variables is the primary factor that has an effect on the surface quality performance metrics in WEDM. As a result of the unsystematic character of machining processes such as the WEDM process, the optimization of input process parameters is an extremely laborious and time-consuming procedure [11]. The coating of the wire electrode can modify the electrical conductivity of the wire electrode. It can alter the discharge energy produced during the machining process. Hence favorable performance measures are possible with the coated wire electrodes in WEDM process [12, 13]. It is essential to develop multi-response optimization strategies in order to identify the WEDM process's most effective parameter combination [14, 15]. Multiple response characteristics can be converted into a sole quality indicator in any process by using one of the available decision-making techniques for multiple performance, such as the assignment of the weight method, genetic algorithms, the Taguchi data envelopment analysis ranking (DEAR) method, or the Taguchi–Grey relation analysis (TGRA). Among them, the TGRA is the most popular choice since it is both very effective and simple to modify. During the course of the materials development process, an effort was made to implement specific TGRA approach as a way of optimizing the parameters of the process. It was discovered that the strategy that has been presented is capable of greatly improving quality measurements [16]. Using the TGRA approach, an ideal combination of grinding process parameters that were involved in the sintering process was discovered. In each given production process, it has been discovered that the TGRA approach is able to find the ideal combination in an efficient manner [17]. To successfully optimize the parameters involved in the robotics-based cutting process, Pillai et al. employed the TGRA approach [18]. It was deduced that the TGRA approach has the capability of computing the optimum process parameters, the importance of which influences the outcomes in the machining processes [19–21]. Using the TGRA approach, one is able to optimize the grinding parameters of environmentally friendly production processes. It has been discovered [22, 23] that the suggested methodology has the potential to improve prediction accuracy. The TGRA technique offers further opportunities for improvement in product design [24]. The in-depth investigation revealed that multi-criteria decision making, also known as MCDM, is the only method that can deliver superior process factors for machining operations. It was also discovered that the WEDM method of machining titanium alloy did not pay a lot of attention to maximizing surface quality performance metrics including white layer thickness, wire wear ratio, and micro hardness. This was one of the things that led to the discovery. When it comes to the construction, the surface has to be of the best possible quality. This goal may be accomplished with the help of multi-criteria decision making (MCDM). In the current investigation, TGRA technique were employed to improve the surface quality indicators achieved by WEDM process while cutting titanium specimens. The following is a list of the major goals that the inquiry on machine-ability using a variety of process parameters tries to achieve.

According to the analysis of the relevant literature that was shown earlier, there are not many studies that make use of a coated electrode in order to carry out an optimization research on particularly on Titanium alloy. This is something that is readily apparent. To be more explicit, the current research contains a comprehensive investigation of the processes that happened throughout the machining process, as well as the link that exists between the electrode conductivity and the performance of the machining. The machining of specimens made of titanium-based alloys has been the subject of a great number of study efforts. On the other hand, not much studies were done to examine how process control factors affect quality metrics when WEDM is used to cut titanium-based alloys. Taguchi-DEAR as a MCDM technique was only seldom used in research endeavors to create WEDM. Consequently, an investigational attempt was conducted to employ this method to maximize the WEDM cutting of certain specimens in order to achieve the following objectives:

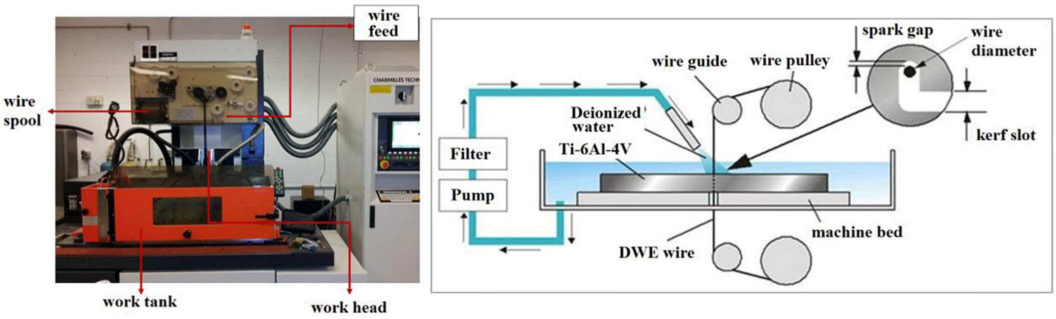
- Using the TGRA as a MCDM to acquire the best possible arrangement of the machining process's control parameters.
- Using a variety of performance measurements, doing an analysis of the effect that process control parameters have on the WEDM process.
- In order to determine which aspects of performance measurements are the most important.

MATERIALS WITH METHODOLOGY

Wire and specimens

Titanium-based (Ti-6Al-4V) alloy (purchased from Bibus Metals, Krakow, Poland) was used in the proposed approach. Titanium and its alloys find widespread application in the biomedical and medical fields: they are immune to corrosion, strong, flexible, and compatible with bone growth. Dental implants, hip and knee replacement surgeries, external prostheses, and surgical instruments are just a few of the medical specifications that titanium is used in. Other industries that titanium and its alloys are used in include the automobile, aerospace, chemical, gas, and food industries [18]. However, due to its initial high cost, limited availability, and ease of manufacture, titanium has certain limitations in its applications. Due to its complicated and challenging extraction and melting processes, titanium is more expensive than other materials. The size of the workpiece specimens in the present study has been considered as 10×10×20.

The WEDM process is significantly impacted by the choice of wire electrode material. Zinc-diffused brass wire electrodes (DCE) with a 0.25 mm diameter were used as tool electrodes because of their specific physical characteristics, as shown in Table 1. With X-ray fluorescence spectroscopy (XRF) equipment made by Bruker Corporation in Massachusetts, the United States, the chemical composition of the titanium alloy is shown in Table 2 below. The diffused



(a) (b)

Figure 1. WEDM setup (a) machine (b) schematic setup

Table 1. Characteristics of wire in present study

Properties	Unit	Traditional brass wire	DCE
Melting point	°C	920	980
Tensile strength	N/mm^2	900	980

Table 2. Chemical composition (Wt %) of the specimen

Elements	C	Fe	Al	O	N	V	H	Ti
Weight %	0.07	0.21	6.10	0.18	0.06	4.05	0.17	Balance

wire electrodes for workpiece machining in the WEDM method are seen in Figure 1. Zinc was applied to a 25 µm-thick layer of brass wire electrode as a coating to minimize wire breakage and electrode wear. Heat treatment was applied to the DCE to cause the coated zinc to melt and firmly adhere to the electrode. The electrical conductivity of the traditional brass wire electrode is affected by adding the zinc coating [12, 13].

WEDM cutting

The examples were cut by Wire EDM machine model of Charmilles 2020 as shown in Figure 1. The parameters that were chosen for the input process were wire tension (WT), servo voltage (SV), peak current (IP), pulse on time (T_{on}), and pulse off time (T_{off}) since they have a significant impact on the machining characteristics. Due to the fact that performance measurements such as material removal rate (MRR), White layer thickness (VLT) and surface roughness (R_a) impact process efficacy, they are used as performance measures of the WEDM process in this research as shown in Figure 2. The deionized water is employed as the insulating medium for performing EDM machining with 4 bar flushing pressure. With a wire feed rate of 5 metres per minute, a dielectric flow rate of 1.2 MPa was used as a constant for all tests. Table 3 displays the aggregated selection of process factors for this investigation. Using a precision scale, the weight was recorded before and after each test run and expressed in millimetres per minute (mm^3/min) to determine the MRR. R_a of the machined specimen was estimated by a non-contact surface roughness tester (TALYSURF CCI LITE) with high pass filtering standard of ISO 4287 standard with perpendicular direction to the cutting direction. The surface topography of machined specimen was extracted by Scanning Electron Microscope (SEM S-3400N).

Taguchi – DEAR technique

Based on the Taguchi approach, the L_{16} orthogonal array (OA) was chosen to perform experiments in WEDM process as the current

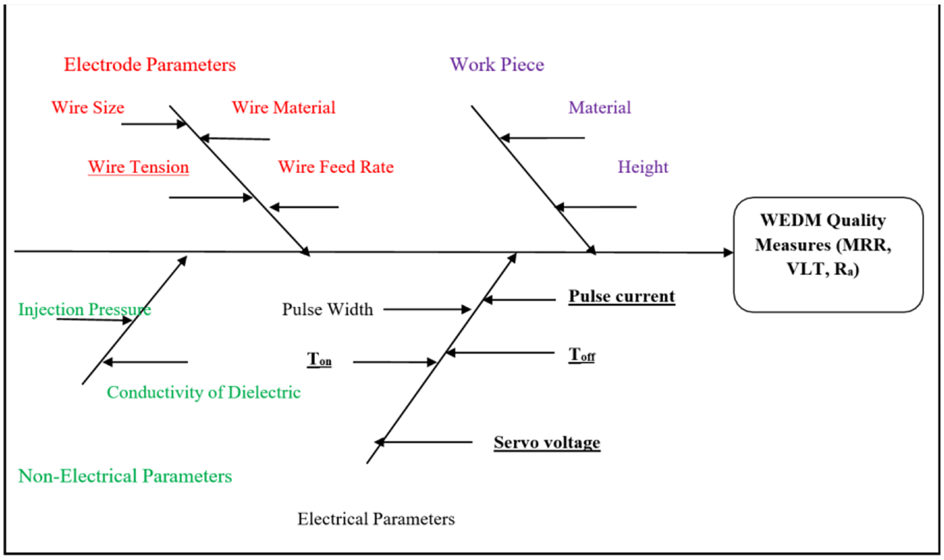


Figure 2. Quality indicators of machined specimen

Table 3. Selection of process factors

Process parameters	Unit	Variables
T_{on}	µs	110, 120, 130, 140
T_{off}	µs	40, 50, 60, 70
SV	V	40, 50, 60, 70
IP	A	3, 4, 5, 6
WT	Kg	6, 7, 8, 9

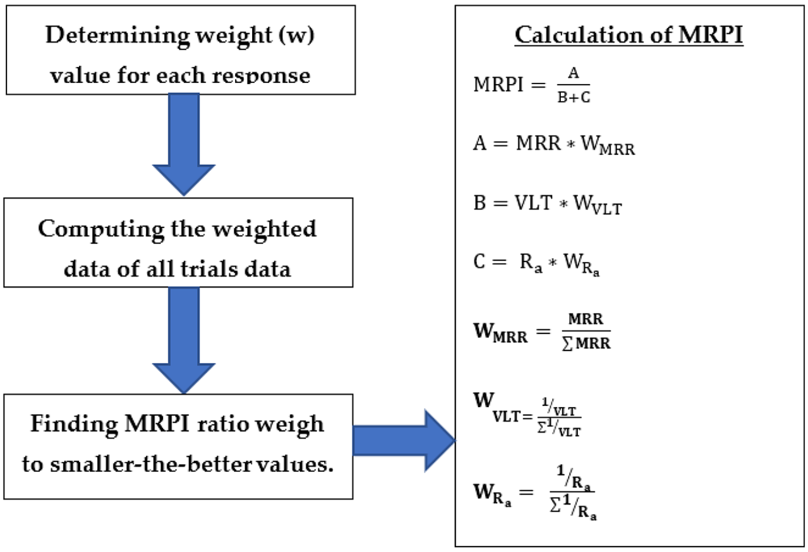


Figure 3. Steps involved in Taguchi-DEAR

study contains 5 input components with 4 levels and two-factor interactions between them. Since the current methodology has been performed with 3 quality indicators, it has been required to adopt MCDM.

The optimal values of the control variables in the proposed DEAR technique may be approximated. To find the best configuration for the control components, this ratio is called the Multi-Response-Performance-Index (MRPI) value. The steps in analysis are shown in Figure 3.

RESULTS AND DISCUSSION

In the present study, 16 cutting experiments were conducted to investigate the effects of WEDM parameters. Each test was conducted four times, with the average representing the ultimate value measured. The experimental responses of all conducted tests are presented in Table 4. In WEDM process, Figure 4 illustrates the morphology characterization of machined specimens with DCE. Specimens exhibiting arcing zones, craters, and recast white

Table 4. Quality indicators in the WEDM

Input factors				Quality measures			
T_{on}	T_{off}	SV	I_P	WT	MRR (mm^3/min)	VLT (µm)	R_a (µm)
110	40	40	3	6	170	1.9	8.8
110	50	50	4	7	180	2.1	10.7
110	60	60	5	8	177	1.9	10.2
110	70	70	6	9	175	1.6	9.8
120	40	50	5	9	210	1.6	8.5
120	50	40	6	8	205	1.7	10.1
120	60	70	3	7	179	1.8	9.7
120	70	60	4	6	184	1.9	10.2
130	40	60	6	6	215	1.8	8.6
130	50	70	5	7	174	1.7	7.5
130	60	40	4	9	178	1.5	10.5
130	70	50	3	8	220	1.8	8.3
140	40	70	4	8	200	1.7	6.8
140	50	60	3	9	185	1.9	7.4
140	60	50	6	6	190	1.8	10.2
140	70	40	5	7	212	1.7	7.1

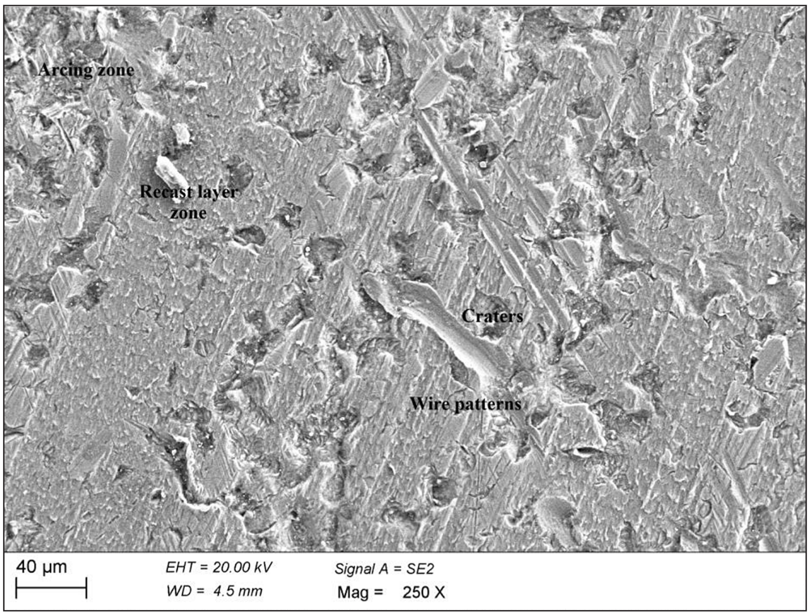


Figure 4. Surface of cut specimens in WEDM

Table 5. Measurement of weights and MRPI

Trial No.	Weights			MRPI
	MRR	VLT	R_a	
1.	0.0557	0.0580	0.0627	14.2885
2.	0.0589	0.0525	0.0516	16.0189
3.	0.0580	0.0580	0.0541	15.4894
4.	0.0573	0.0689	0.0563	15.1414
5.	0.0688	0.0689	0.0649	21.8036
6.	0.0671	0.0648	0.0547	20.7777
7.	0.0586	0.0612	0.0569	15.8414
8.	0.0602	0.0580	0.0541	16.7388
9.	0.0704	0.0612	0.0642	22.8542
10.	0.0570	0.0648	0.0736	14.9688
11.	0.0583	0.0735	0.0526	15.6649
12.	0.0720	0.0612	0.0665	23.9295
13.	0.0655	0.0648	0.0812	19.7765
14.	0.0606	0.0580	0.0746	16.9212
15.	0.0622	0.0612	0.0541	17.8483
16.	0.0694	0.0648	0.0778	22.2208

layer portions show the wire electrode patterns. The white area shows that there is zinc concentration in the wire electrode. The zinc particulates were deposited on the surface that had been machined.

Effects of process parameters on quality indicators

The MRPI values and weights associated with each outcome parameter are presented in Table 5. It was hypothesized that trial number 12 would be able to eradicate a greater quantity of material at a lower VLT and R_a. The amount of particles that is removed is related to the amount of time that the pulse on. Because of this, the longer pulse on time has the potential to yield a greater MRR. Because the T_{off} has a role in the deionization process that occurs after the machining mechanism, an increase in the T_{off} might result in a reduction in the R_a. The voltage of the servo can make a significant contribution to the VLT. A reduced kerf width may be produced by using a servo voltage that is moderate. As a result, experiment number 12 could be able to create a greater MRR while maintaining a lower VLT and surface roughness in the cut surface of the specimens by utilizing the WEDM method with DCE.

Influential process factors

To determine which components are most important by using the consolidated MRPI idea, it is possible that a different grouping provide more accurate performance measurements than trial 12. Table 6 illustrates the aggregated MRPI of the control variables, along with the values that correspond to those variables. The larger level value of each process component was used to establish the ideal level of input factors that should be used for developing quality measures. As a result of looking at Table 5, one may draw the conclusion that the ideal levels of process factors for the current experiment are levels 3, 1, 2, 4 and 3 for T_{on}, T_{off}, SV, I_P and WT, respectively. The MRPI values for the WEDM process with numerous different combinations of process control variables were calculated by using the Taguchi-DEAR approach. When it comes to machining operations, the larger value represents the optimal level of the corresponding factor, which is determined by a variety of quality indicators. According to the findings shown in Table 7, the optimal formation of process control variables being investigated in this research was determined to be 130 μs (T_{on}), 40 μs (T_{off}), 50 V (SV), 6 A (I_p), and 8 kg (WT). Because of this, the longer pulse on time has the potential to yield a greater MRR. Because the pulse-off time is a contributing factor in the deionization process that occurs after the machining mechanism, a longer T_{off} has the potential to generate a surface with a lower roughness level. It is possible for the form DCE to modify the overcut. The reduced tension in the wire produces a smooth and conservative wire that has been brought closer to the specimens. As a result, it is capable of producing a reduced kerf width. The largest difference between the maximum and the minimum value demonstrates the greater relevance of the process control factors. It was found that the T_{on} possesses greater relevance in defining the quality measures owing to the fact that it is so important for deionization. Following each pulse discharge, the deionization procedure has to be carried out. After that, only subsequent charging phase will be able to be effectively completed in order to improve the mechanism of removal. As a result of the fact that the flushing process occurs during the T_{off}, it has the potential to favorably affect the quality measurements.

Confirmation of the optimized parameters

In a trial for confirmation, the conclusions that were achieved through the analysis need to be verified. Once again, the experimental test was carried out using the most appropriate proportions of all of the significant factors

Table 6. Mean MRPI values

Parameters	Levels				Max – Min
	1	2	3	4	
T_{on}	15.2346	18.7904	19.3544	19.1917	4.1198
T_{off}	19.6807	17.1717	16.2110	19.5076	3.4697
SV	18.2380	19.9001	18.0009	16.4320	3.4681
I_P	17.7452	17.0498	18.6207	19.1554	2.1056
WT	17.9324	17.2625	19.9933	17.3828	2.7308

Table 7. Optimal factors

Factors	Variable	Unit
T_{on}	130	μs
T_{off}	40	μs
SV	50	V
Peak current	6	A
Wire tension	8	Kg

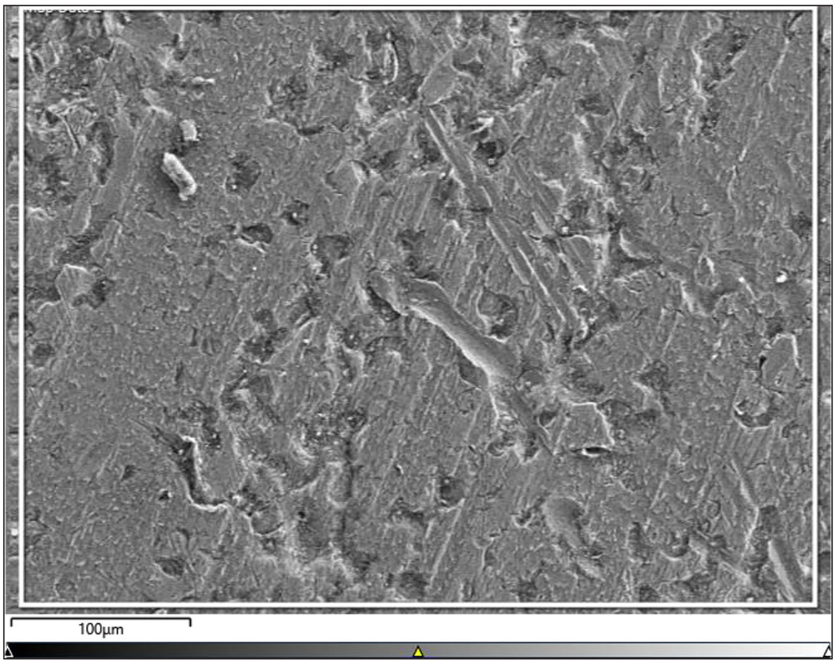


Figure 5. SEM based surface analysis

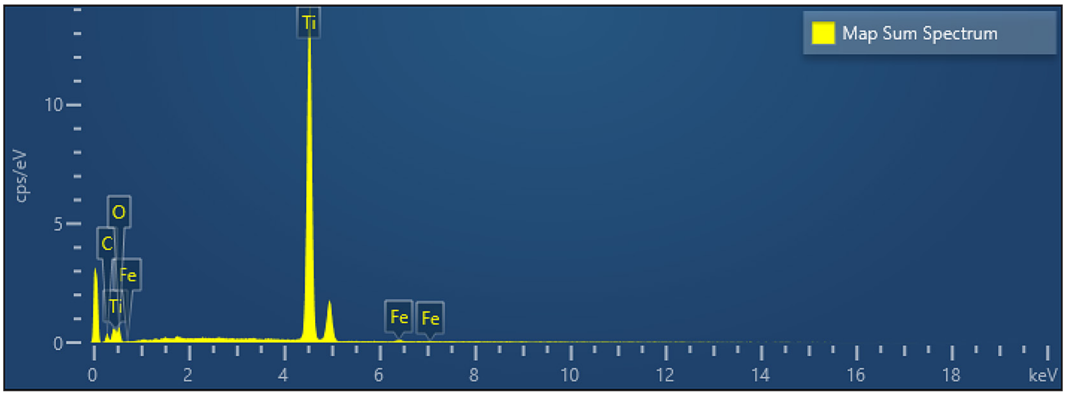


Figure 6. EDS analysis of machined specimen under optimal process factors

[27]. The findings of the conformation tests that were carried out under the circumstances that had been computed were as follows: 215 mm^3/min (MRR), 0.7 mm (VLT) and 9.2 µm (R_a). The MRPI value for the confirmation trial was 2.7% different than the value that was considered the mean. As a result, the correctness of the prognosis was shown.

Investigation of surface morphology

The microstructural analysis was looked at, and a comparison was made with trial 12. Figure 5 depicts the surface morphology seen by SEM after the WEDM procedure was carried out at the optimal machining settings. Over the surface that has been machined, the molten particles are resolidified, creating what is known as WL [26]. The surface quality of the specimens might be affected by the thickness of the layer that is being applied. Over the machined surface, it was noticed that there was just a little layer of resolidified material. This was a significant finding. Figure 6 depicts the surface morphology as determined by an energy-dispersive X-ray spectroscope (EDS) when the WEDM procedure was carried out using the optimum parameters. On the machined surface, it was discovered that there were far less carbon particles than before. As a result, it was discovered that almost no arcing took place during the process of machining as a result of adequate deionization combined with an improved mechanism for material removal [27, 28].

CONCLUSIONS

An attempt was performed to use DEAR methodology while cutting Titanium alloy using DCE in WEDM. This was done in order to get optimal results. From this, it was able to make the findings that are shown below.

1. The proposed process under optimal factors can machine the specimens with small amount of recast white layer area, craters, and arcing zone.
2. Among the factors that were chosen, the ideal arrangement of input factors in the WEDM process was discovered to be 130 µs (T_{on}), 40 µs (T_{off}), 50 V (SV), 6 A (I_P) and 8 kg (WT) with the error accuracy was 2.7%.
3. Because of the role it plays in the deionization process, the pulse on time is the most important factors to consider when determining the quality of the output.
4. The importance of other appropriate coated electrodes under different optimization approaches may be investigated on performance measurements by applying the WEDM procedure.

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