Investigation of Response Parameters on Vibration Assisted Micro-Edm on Ti–6Al–4V Alloy

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Abstract

Micro EDM is a versatile process that is effectively used for machining hard and difficult-to-cut materials including superalloy. It is a recently developed process for producing micro-parts with dimensions ranging from 50 to 1000 µm. Micro-EDM is a cost-effective machining technology for creating a micro-metal hole that is used in orthopedic implants. In this work, Micro EDM experiments are carried out on the material Ti-6Al-4V. This material finds wide applications in biomedical industries for making dental bone replacement applications. Low-frequency Vibrations have been applied to remove the debris from the machining zone. A brass tool of 400 µm diameter is used as a tool electrode material. Micromachining (Micro drilling) is a challenging task because of the small size of the tool. In this work, micro drilling has been attempted with 400 microns tool and thereof tool wear and hole quality have been investigated. The detailed investigation of MRR (MRR), TWR (TWR), Surface Roughness (Ra), and Overcut (OC) have been carried out using Micro-structural analysis, SEM Studies, and EDS analysis. It is found that various parameters have some effects on the hole quality and tool wear. An attempt has been made to find out optimum parameter settings using statistical tools and the Design of experiments.

Keywords
Micro-EDM, Micro drilling, Bio-medical, Statistical analysis and SEM-EDS.

1. Introduction
Micro EDM is a versatile process that is effectively used for machining hard and difficult-to-cut materials. In this machining process, the machine removes material at a very small level smaller than 100 m. The amount of electricity required is very low in micro EDM than in other EDM since the machining takes place at very nano or micro levels. Micro-EDM is used in machining techniques such as micro-wire EDM, micro-EDM drilling, and micro-EDM milling. Micro-wire EDM uses a wire with a diameter of less than 20 m. Other micro-EDM technologies have minimum machinability of 5 m for cavities. Micro EDM properties are influenced by the grain sizes of workpiece materials.

Nomenclature

MRR	Material Removal Rate
TWR	Tool Wear Rate
DA	Dimensional Accuracy
SEM	Scanning Electron Microscopy
EDS	Energy Dispersive Spectroscopy

EDM is a very versatile process it is used in the machining of various materials. This research aims to utilize Micro EDM for machining of Bio Materials and analyze the effect of machining on the behavior of the material in various aspects. The Titanium alloy has a very refined grain structure thus it may provide us with the required surface finish. Also, the applications require accurate machining which can be done on Micromachining. Very less research is being carried out at such a micro level of machining because of various challenges in the making of tools and availability of machines, thus it is needed to carry out further research in the area of micromachining in general and Micro EDM in specific.

2. Literature Review

Jaber E. Abu Qudeiri et al. (2019) describes theoretical and experimental EDM studies that have aims to enhance the performance of the process by taking into consideration, among several other things, MRR, surface finish, and TWR. The usage of EDM for different grades of stainless steel materials was developed. The main factors affecting the MRR and EWR, in that order, are discharge current, electrode wear, and pulse duration time. Lower pulsed current and pulse-on time values produced a better surface finish.

Annamalai et al. (2014) developed the evolution of techniques and procedures for transforming Ti6Al4V into a material that can be used for biomedical purposes. This material's biocompatibility has been evaluated and presented. Ti6Al4V conversion experiments into suitable material for biomedical applications are consolidated.

Anthuvan and Krishnaraj (2022) developed a way to mitigate debris buildup in the sparking zone and optimize the machining of micro-holes utilizing EDM. The work attempts to build a hybrid procedure using two methods in succession. To discover the best parameters combining the output responses MRR and DA, the process parameters input current, pulse on time, and pulse off time were examined in this experimental work.

Maninder Singh and Shankar Singh (2021) Tool material, discharge current, servo voltage, and pulse duration was changed as input parameters during the experiment to determine their impacts on MRR and SR. While processing Nimonic alloy 75 work material, a comparison between traditional EDM and UAEDM techniques was studied.

Pramanik et al. (2020) developed various EDM procedures used to mill titanium alloys, including wire EDM, die-sink EDM, EDM drill, and hybrid EDM. All of these techniques' machining mechanisms, tool electrodes, dielectrics, materials removal rate, and surface integrity are critically examined.

Kumar et al. (2018) developed the ideal working conditions for an electro discharge machine used to bore out aerospace material (Inconel 718) Peak current, pulse on time, pulse off time, orbital speed, and orbital radius are determined to be the characteristics for overcutting, while peak current, pulse on time, pulse off time, and orbital speed are discovered to be the parameters for surface roughness.

Mahendran et al. (2014), the properties of the Micro-EDM process, as well as the parameters of MRR and TWR, are discussed in this study. The fundamentals of micro-EDM, various EDM processes, dielectric fluid, different generator types, EDM process parameters, MRR (MRR), and tool wear ratio are the main topics of this paper (TWR). The progress of the research for the fabrication of the micro-EDM with the microactuator tool feed mechanism machine depends on the findings of this study.

D'Urso et al. (2016), while studying the micro electro discharge drilling of 316L stainless steel using copper tubular electrodes, the exchanged power was considered as a comprehensive variable that could depict the impact of the peak current and voltage on the outcome. The impact of the actual process parameters on the effectiveness of the stainless steel micro-EDM drilling technique was examined. To examine the impact of electrode size on the geometrical properties of the micro-holes and on the process performance, copper electrodes with varying diameters were utilized.

Siva et al. (2014), this study examines the micro EDM using brass and D2 steel as electrodes. In this test-and-find project. Current, voltage, pulse on time, and capacitance were chosen as the input process parameters. On a workpiece with a hole that was 0.5 mm in diameter, experimental research was done. It was determined how input factors affected the rates of material removal, electrode wear, overcutting, and tapering. The findings suggest that current is the most important variable influencing how MRR, EWR, taper angle, and overcut are affected.
SeongMin Son et al. (2007), this study investigated the impact of the EDM pulse condition on the micro EDM characteristics. According to the experimental findings, the voltage and current of the pulse have a significant impact on the machining characteristics, and a shorter EDM pulse is more effective at producing precision parts with greater MRR. Han et al. (2005), the smallest scale at which machined parts can be produced as well as the variables affecting the creation of sub-micrometer parts were looked into. The results show that sub-micrometer machining is not suited for the smallest discharge energy, insufficient positioning accuracy, or the inaccurate machined shape brought on by the influence of gap management and thermal deformation.

Li et al. (2022) to understand the driving force for bubble movement or escape in the small gap and to evaluate the evolution of the bubble flushing effect with increasing hole depth, the bubble flushing effect is carefully explored in this study. Li et al. (2022), this study presents a novel micro-EDM technique that replaces the conventional rotating electrode with a two-dimensional ultrasonic circular vibration electrode to improve the surface integrity of Ti-6Al-4V from the standpoint of raising the relative velocity between electrode and workpiece to improve the surface integrity in micro-EDM. Singh and Bharti (2022), the current study uses experimental methods to look into reactions like drilling rate and TWR. For drilling tiny holes in titanium alloy using a brass tool during electric discharge machining (EDM). Response surface methodology-based central composite design is used in the tests.

Choubey and Maity (2019), in this study, the MRR and crater are modeled using finite elements for micro-electrical discharge machining both with and without workpiece vibration. The vibration of the workpiece during the micro-EDM process increased the effectiveness of flushing and the rate of material removal. The numerical model's MRR results showed that the MRR in micro-EDM with vibration was improved over that in micro-EDM without vibration. Mertiya et al. (2021), in this work, a low-frequency vibration platform was developed to support vibrations in the 0-100 Hz range, which will improve the performance of EDM. The low-frequency workpiece vibration contributed to an improvement in the surface finish through enhanced flushing at the discharge gap and debris elimination. However, it was discovered that the MRR and TWR could not be improved and reduced sufficiently at frequencies below 100 Hz. Davis et al. (2021), in this study, bioactive zinc powder particle concentrations (PPCs) of 0, 2, 4, 6, 8, and 10 g/l were added to the dielectric to modify the existing capabilities of a conventional micro-electric discharge machining (-EDM) setup. Significant improvements in the surface characteristics of PM-EDMed Ti-6Al-4V alloy specimens were made thanks to the improved machining capabilities of -EDM utilizing zinc powder particles.

2.1 Objectives

In the literature survey it has been found that there is a research gap in the identification of proper biomaterials and their micromachining which includes analysis of MRR (MRR), TWR (TWR), and dimensional accuracy of the required hole which is used in many biomedical applications.

The work undertaken has multiple objectives as follows:

- To carry out an experimental Investigation & comparison of process parameters of Electric Discharge Machining and its results.
- To analyze the machining behavior of Ti-6Al-4V Alloy.
- Assessment of Ti-6Al-4V with Brass electrode in EDM.
- To study the different process parameters affecting the Micro Electric Discharge Machining performance with Statistical Analysis and optimization.

3. Methods

In this research, a rectangular block of titanium alloy Grade 5 with a thickness of 0.5 mm and a composition of Ti-6Al-4V is employed as the work material. Particularly Ti-6Al-4V, a titanium alloy, has special metallurgical characteristics. This research is employed to investigate its behavior with Micro EDM and its applications in the Bio-Medical industry by producing micro holes in it. Titanium alloys are widely utilized in a variety of applications, including those involving medical devices such as body part transplants, dentistry, and several sub-critical components. Pure Brass having good conductivity is used as the electrode material. The Taguchi design of the experiment (L9) was followed when performing EDM on Ti-6Al-4V samples, and the effects of voltage (V), capacitance (C), speed (RPM), vibration (Hz) on TWR, MRR, and overcut were examined (Table 1 and Table 2).

Table 1. Chemical Composition of Ti-6Al-4V.

Element	Ti	Al	V	Fe	O	C	N	H
Content (%)	87.6	5.5	3.5	0.40	0.`20	0.080	0.050	0.015

Table 2. Chemical Composition of Brass.

Element	Cu	Zn	Fe	Pb
Content (%)	94.0	5.90	0.05	0.05

3.1 Experimental Setup

For the EDM of Ti-6Al-4V, Micro-Tools' Hybrid DT-110i EDM, a PC-based CNC Controlled device, was employed. The electrode used in this investigation was 400 mm in diameter and mm long. Pure brass made up the entirety of it. The electrode was created in two steps, the first of which entailed cutting the electrode with a very accurate wire cut EDM to a length of 2 mm. In the second stage, the tip received additional machining utilizing the turning process to achieve the final diameter of 0.400 mm. Each electrode measured 2 mm in length, with a 400 mm tip and an additional 50 mm for clamping it in the chuck.

To measure MRR and TWR, the sample weights (Figure 1 and Figure 2) were precisely measured both before and after machining. The Electronic Precision Balance was used, a high-precision digital weighing balance that is exceptionally sensitive and accurate to 0.0001 g. The balance was kept in a glass cage to prevent environmental pressure changes from having an impact on the final reading. The response MRR and TWR are calculated using Equations 1 and 2 .

Figure 1. Workpiece material.

Figure 2. Brass tool of dia. 400 microns.

$$\text{MRR} = \frac{\text{Volume of material removed fromworkpiece}}{\text{Machining time} \times \text{Density of work material}} \quad \text{.....(1)}$$

$$\text{TWR} = \frac{\text{Volume of material removed f rom electrode}}{\text{Machining time} \times \text{Density of electrode material}} \quad \text{.....(2)}$$

The sizes of the machined holes were measured using a polarised optical microscope to get the diametrical precision The difference between the entry diameter of the microhole and the microtool was used to evaluate the diametric acc uracy (overcut).

Eq. 3 gives an accurate interpretation of Overcut Measured.
$DA = D - Dt$ .....(3)
where D is the actual diameter and Dt is the tool diameter.

3.2 Experimental Procedures

The experimental planning process used the L9 orthogonal array. Table displays the control variables and their varied values that have the most effects on the response parameters. The parameter design was created to find the best conditions for achieving acceptable precision, maximum MRR, and minimal TWR. It also served to determine the impact of the input parameters on the machining process. Based on a review of the literature and preliminary experimental tests, the input parameters and each level employed in the experimental design were chosen. The tests were carried out, and using Equations 1. 2 and 3, the output responses MRR, TWR and Overcut were calculated. Table shows the preliminary experimental findings (Table 3 and table 4).

Table 3. Selected input parameters and their levels for experiments.

Sr. No	Input parameters	Level 1	Level 2	Level 3
1	Voltage (V)	100	110	120
2	Capacitance (nF)	4	5	6
3	Speed (RPM)	1000	1500	2000
4	Vibration (kHz)	40	80	120

Table 4. Experimental machining conditions

Workpiece	Ti-6Al-4V Alloy
Electrode	Brass
Dielectric Medium	EDM-50 Oil
Size of electrode Material	Diameter= 400 microns, Length= 2 mm

4. Data Collection

The Tool wear and MRR is calculated using Electronic Weighing machine upto precision of 0.0001 accuracy (Figure 3-11). The initial and final weight of tool and workpiece is noted and MRR and TWR is calculated using formula given in equation (1) and (2) (Table 5).

Figure 3. Weighing machine used for MRR and TWR.

Table 5. Input and Output Parameters with GRG.

	Process Parameters				Response Parameters				
Trial No.	**Voltage (V)**	**Capacitance.(nF)**	**Speed (RPM)**	**Vib. (kHz)**	**MRR (in gm)**	**TWR (in gm)**	**Overcut**	**GRG**	**Rank**
1	100	4	1000	40	56.70843	40.099509	235.7	0.58833	**5**
2	100	5	1500	80	8.3626439	39.00564	325.5	0.47333	**9**
3	100	6	2000	120	3.1050313	6.901065	290.1	0.55896	**7**
4	110	4	1500	120	84.6942019	134.0797923	185.1	0.65511	**3**

5	110	5	2000	40	17.1874697	32.4556083	160.9	0.58399	**6**
6	110	6	1000	80	4.258116	11.65455	77.8	0.7558	**1**
7	120	4	2000	80	50.66148	199.67256	150.2	0.5032	**8**
8	120	5	1000	120	33.06552	30.86055	160.4	0.60937	**4**
9	120	6	1500	40	6.71145	4.40865	90.6	0.74993	**2**

5. Results and Discussion

5.1 MRR

Table 6. Analysis of Variance of MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	5721.52	1430.38	5.86	0.058
Voltage (V)	1	82.60	82.60	0.34	0.592
Capacitance.(nF)	1	5280.04	5280.04	21.61	0.010
Speed (RPM)	1	88.77	88.77	0.36	0.579
Vib. (kHz)	1	270.11	270.11	1.11	0.352
Error	4	977.19	244.30		
Total	8	6698.71			

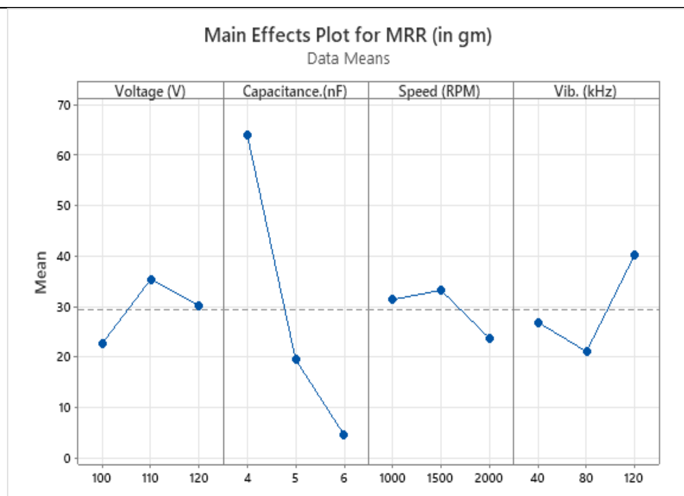

Figure 4. Mean Effect plot of MRR

Regression Equation of MRR:
MRR (in gm)= 135.0 + 0.371 Voltage (V) - 29.66 Capacitance.(nF) - 0.0077 Speed (RPM) (Table 6)
+ 0.168 Vib. (kHz)

5.2 TWR

Table 7. Analysis of Variance of TWR

Source	DF	Adj SS	Adj MS	F-Value	P-Value

Regression	4	29795	7449	5.22	0.069
Voltage (V)	1	3697	3697	2.59	0.183
Capacitance.(nF)	1	20520	20520	14.38	0.019
Speed (RPM)	1	4078	4078	2.86	0.166
Vib. (kHz)	1	1500	1500	1.05	0.363
Error	4	5707	1427		
Total	8	35502			

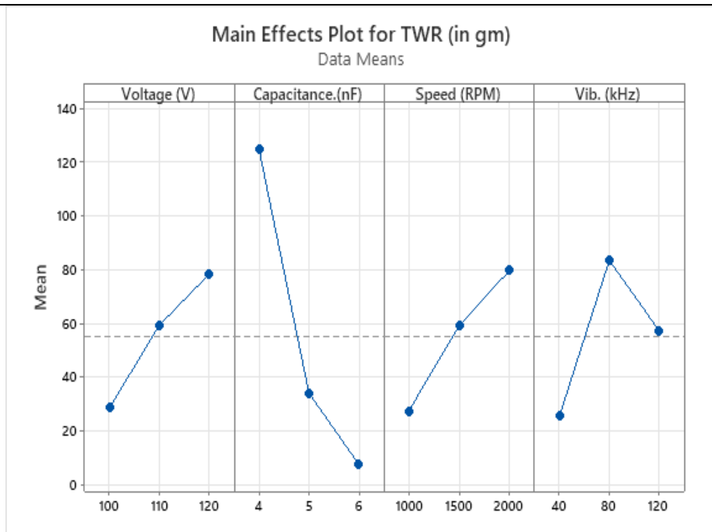

Figure 5. Mean Effect plot of TWR.

Regression Equation of TWR:
TWR (in gm)= -35 + 2.48 Voltage (V) - 58.5 Capacitance.(nF) + 0.0521 Speed (RPM)+ 0.395 Vib. (kHz) (Table 7)

5.3 Overcut

Table 8. Analysis of Variance of Overcut

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	42246	10561	3.04	0.153
Voltage (V)	1	33765	33765	9.72	0.036
Capacitance.(nF)	1	2109	2109	0.61	0.479
Speed (RPM)	1	2701	2701	0.78	0.428
Vib. (kHz)	1	3670	3670	1.06	0.362
Error	4	13897	3474		
Total	8	56143			

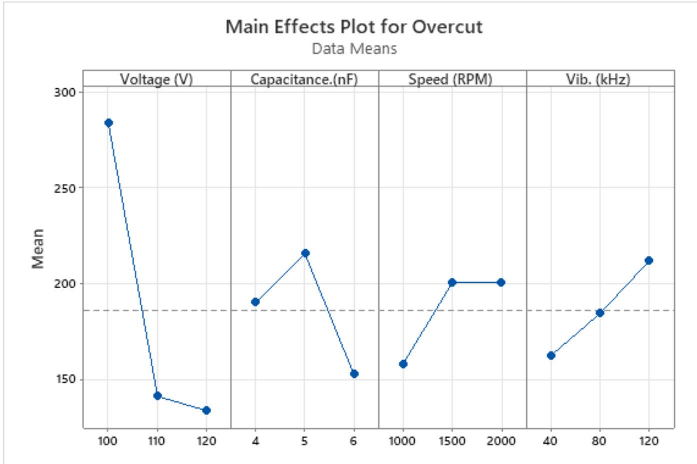

Figure 6. Mean Effect plot of Overcut

Regression Equation of Overcut:
Overcut = 992 - 7.50 Voltage (V) - 18.7 Capacitance.(nF) + 0.0424 Speed (RPM) + 0.618 Vib. (kHz) (Table 8)

5.4 Multi objective optimization

Grey relational analysis, a multi-response optimization technique, was utilized to resolve interrelationships among the various responses in order to arrive at an ideal parameter that combined the responses' MRR, TWR and diametrical precision (Table 9).

The larger-the-better MRR, smaller-the-better TWR, and smaller-the-better diametrical precision are the favorable circumstances for output responses in this work. For assessing the relational degree of the various responses, these are used to generate grey relational grades.

Table 9. Optimum combination predicted from GRA.

Voltage (V)	Capacitance(nF)	Speed (RPM)	Vib. (kHz)	MRR (gm)	TWR (gm)	Overcut	GRG
110	6	1000	80	4.258116	11.65455	77.8	0.7558

Thus, can be found that the optimal values are Voltage = 110 V, Capacitance = 6 nF, Speed = 1000 rpm and Vibrations = 80kHz.

5.5 Overcut and Dimensional Accuracy

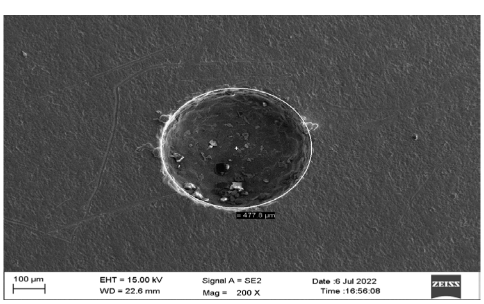

Figure 7. Overcut of Hole no 6 (Best Hole)

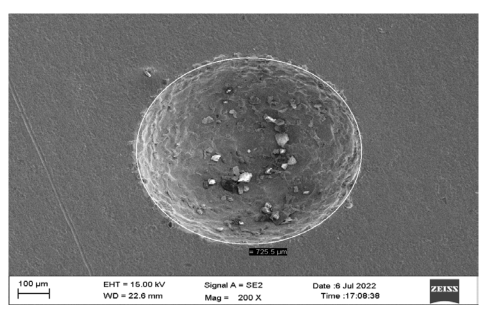

Figure 8. Overcut of Hole no2 (Worst Hole)

The excess diameter made by the tool because of variations such as diametral offset and uneven cutting during working conditions is called an Overcut. Overcut is measured from SEM images in which actual diameter is calculated and overcut is given by equation no. (3). Images show the best hole with a diameter of 477.8 microns and the worst hole with diameter of 725.5 microns.

5.6 Tool wear and Analysis

The images are captured in an optical microscope which is mounted on the machine. It is evident that the tool wear occurs during the machining and is deposited in the hole made in the workpiece. Thus the images of the tool after machining are captured. The deposits of the tool are studied under SEM and EDS analysis is done to measure the number of tool deposits.

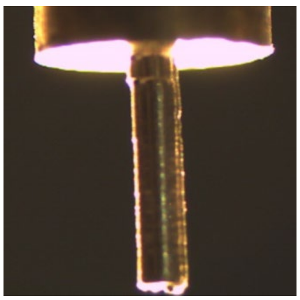

Figure 9. Initial tool image

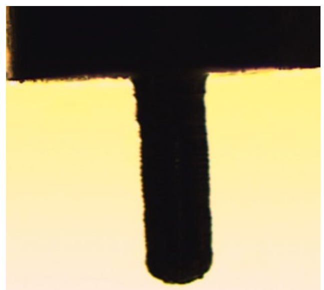

Figure 10. Tool wear for 6 (Best Hole)

Figure 11. Tool wear for 8 (Worst Hole)

5.7 SEM and EDS Analysis

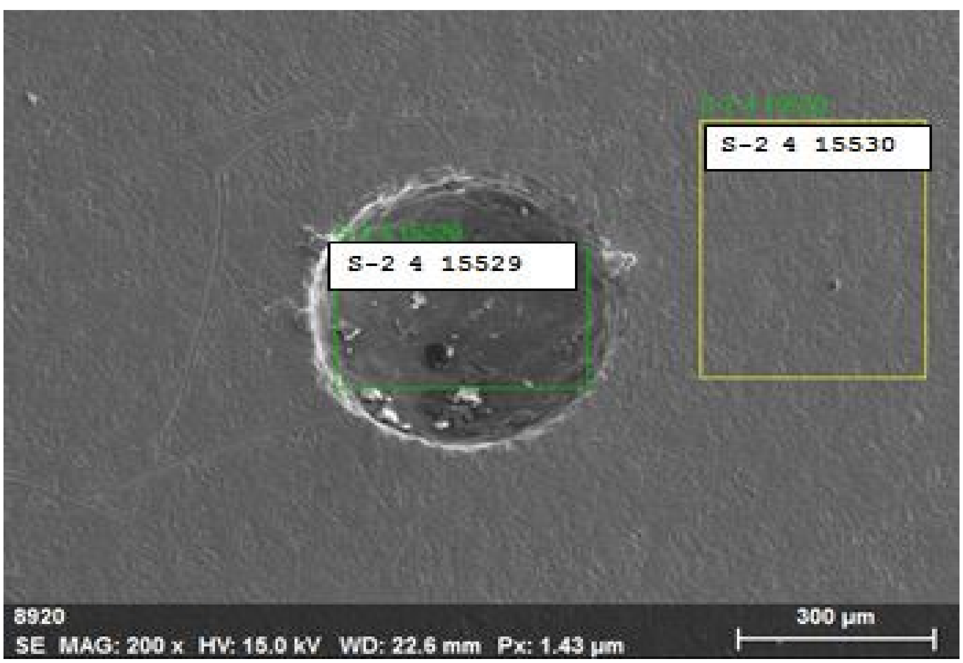

Figure 12. EDS Analysis of Hole no. 6 (Best Hole)

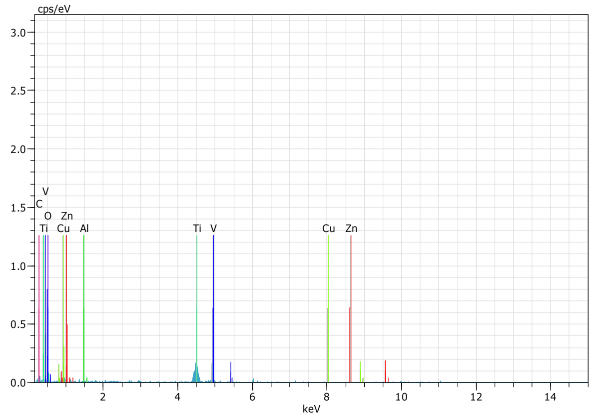

Figure 13. EDS Analysis graph of S-2 4 15529

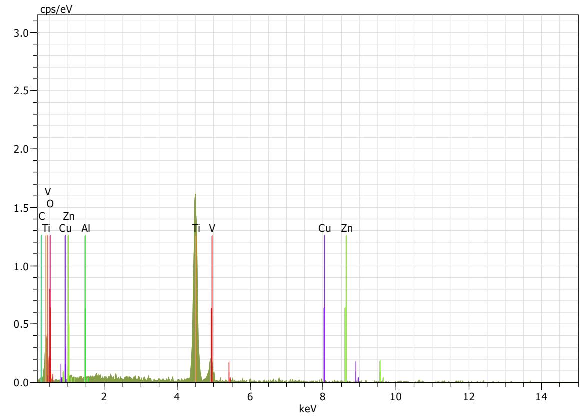

Figure 14. EDS Analysis graph of S-2 4 15530

Spectrum: S-2 4 15529

El	AN	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
Ti	22	K-series	56.08	58.97	32.00	4.60
O	8	K-series	19.64	20.65	33.54	22.19
C	6	K-series	14.07	14.80	32.02	12.55
Cu	29	K-series	2.62	2.75	1.13	1.88
Zn	30	K-series	2.37	2.49	0.99	2.07
Al	13	K-series	0.31	0.33	0.32	0.23
V	23	K-series	0.00	0.00	0.00	0.00
Total:			95.09	100.00	100.00	

Spectrum: S-2 4 15530

El	AN	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
Ti	22	K-series	92.38	96.37	89.38	3.56
C	6	K-series	2.18	2.27	8.39	2.03
Cu	29	K-series	0.69	0.72	0.51	0.39
O	8	K-series	0.59	0.62	1.71	1.76
Zn	30	K-series	0.01	0.01	0.01	0.08
V	23	K-series	0.00	0.00	0.00	0.00
Al	13	K-series	0.00	0.00	0.00	0.00
Total:			95.85	100.00	100.00	

Figure 15. Scanning Electron Microscopy (SEM)

From the above images (Figure 12-15) taken from Scanning Electron Microscopy (SEM), it is evident that a significant amount of tool wear deposits are accumulated in the hole. They can contribute to changes in the chemical behavior of the base material and may not provide accurate results.

EDS analysis shows the chemical composition of the workpiece and the chemical composition of the tool deposited in the hole.

6. Conclusion

The main conclusions that are observed during the experiments are as follows:

- The most significant parameter observed is Capacitance for MRR and TWR and Overcut is most significantly dependent on Voltage variations.
- As MRR is higher the better, it is found that it increases with Voltage and Vibrations and decreases with Capacitance and rotational speed.
- For TWR, it is lower the better thus it decreases with a decrease in Capacitance and increases with an increase in Voltage, rotational speed, and Vibrations.
- Overcut implies Dimensional Accuracy of the Hole, thus it should be lower as possible which is obtained when Voltage and Capacitance increase but decreases with an increase in speed and Vibrations.
- Brass has good electrical conductivity and bending strength, it is a good option as a microelectrode material.

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Biographies

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