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Experimental investigation on Material removal rate and Kerf width of heat treated Ti-6Al-4V machined by WEDM

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***Abstract**: In this study the Ti-6Al -4V is heat treated at 1100ºC followed by water quenching to improve its hardness .Then the hardened specimens of Ti-6Al-4V is machined by WEDM on different process parameters . Experiments were conducted based on Taguchi's method and as per $L_{25}(5^6)$ orthogonal array while considering six controllable factors (i.e. parameters), with five levels each. The important machining parameters of WEDM which effects the surface roughness is Pulse -On time, Pulse - off time ,Peak current and Servo voltage. In this research WEDM experiment using 0.25 mm diameter brass wire is used. The predicted optimal setting of process parameters for material removal rate, kerf width has been obtained and analyzed by using Taguchi method. SEM anaylsis has been done on the specimen with highest material removal rate and lowest material removal rate.*

***Keywords**: Wire electrical discharge machining (WEDM),Material removal rate(MRR),Kerf width(KR),Taguchi method.*

I. Introduction

Titanium and titanium alloys have a wide range of applications in aerospace, energetic, chemical and automobile industry. Some titanium alloys are excellent materials for biomedical use, especially as orthopedic alloys. The most important characteristic features of these biomedical titanium alloys are high strength, low density, excellent corrosion resistance and the best biocompatibility among the metallic biomaterials. The Ti6Al4V alloy, originally having been developed as a construction alloy for aircraft industry, belongs to the most significant alloys within the implant alloys for hard tissue replacement [1]. Ti–6Al–4V alloy has two allotropic phases, namely, the body centered cubic (BCC) structured b phase and the hexagonal close-packed (HCP) structured a phase. The b phase distributes along the boundaries of a phase. It contains 6% aluminum for a stabilization and 4% vanadium for b stabilization, and when it is heated up to 882 ºC, a phase transforms to b phase [2,3] Within the family of titanium alloys, the α+β alloys are the most widely used because of the great variety of microstructures and mechanical properties that can be obtained by varying their composition and thermo mechanical treatments [1].One of these α+β alloys has the greatest commercial importance namely Ti-6Al-4V, making up more than half of the sales of titanium alloys [2].
WEDM is a thermo- electrical process in which material is removed by a series of sparks between work piece and wire electrode (tool). The part and wire are immersed in a dielectric (electrically non conducting) fluid, usually deionized water, which also acts as a coolant and flushes the debris away. The material which is to be cut must be electrically conductive.

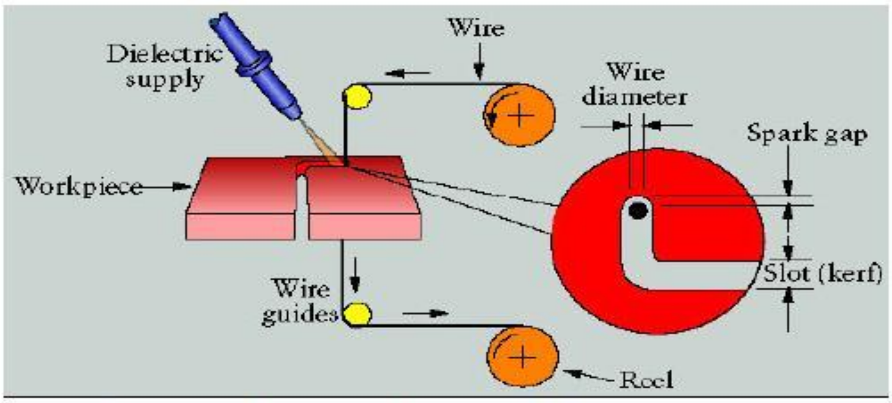

Figure 1. Working principle of WEDM [23]

In WEDM, there is no direct contact between workpiece and tool (wire) as in conventional machining process, therefore materials of any hardness can be machined and minimum clamping pressure is required to hold the workpiece. In this process, the material is eroded by a series of discrete electrical discharges between the workpiece and tool. These discharges cause sparks and result in high temperatures instantaneously, up to about 10000º C. These temperatures are huge enough to melt and vaporize the workpiece metal and the eroded debris cools down swiftly in working liquid and flushed away, the working principle is shown in the figure 1.The effectiveness of the whole process depends on number of input process parameters such as pulse on time, pulse off time, servo voltage, peak current, dielectric flow rate, wire feed, and wire tension. The important machining responses include material removal rate (MRR), surface roughness (Ra), Kerf (width of cut), wire wear ratio (WWR) and surface integrity factors [5].

II. Literature review

Dhruv.h Gajjar et al [6] found that pulse on time at level 3 (130 µs), pulse off time at level 3 (60 µs), servo voltage at level 2 (30volts) are the best process parameter for the MRR, KERF width and Surface roughness for machining of Ti-6Al-4V using WEDM. Pulse off time has opposite effect to pulse on time.MRR decrease with increase of pulse off time, while surface roughness reduces. Surface roughness reduces with increase of servo voltage. Vijaybabu.T et al [7] described an optimum cutting parameters for Titanium Grade5 (Ti-6Al-4V) using Wire-cut Electrical Machining Process (WEDM). The response of Volume Material Removal Rate (MRR) and Surface Roughness (Ra) were considered for improving the machining efficiency. It was observed that the pulse on time, and peak current are the most significant factors for the performance measures. The wire tension, servo voltage and servo feed settings are less significant on performance measure. Reham Reda et al. [8] studied the effect of water quenching on mechanical properties of cast Ti-6Al-4V alloy. Tensile, hardness and charpy impact toughness tests were performed. The samples were heated up to different temperatures in α+β range (900°C, 935°C, 980°C), then isothermally held for 10 minute, followed by water quenching. The results showed that the final properties of cast Ti-6Al-4V alloy are highly dependent on the quenching temperature. Mechanical properties of Ti-6Al-4V cast alloy are affected considerably by heat treatments and developed microstructures. Lokeswara Rao T. [9] Evaluated the effects on machining parameters on volume material removal rate, surface roughness on Titanium Grade5 (Ti-6Al-4V) using Wire-cut Electrical Machining Process (WEDM). The Experimentation has been done by using Taguchi's L25 orthogonal array (OA) under different conditions like pulse on, pulse off, peak current, wire tension, servo voltage and servo feed settings. Regression equation is developed for the VMRR and Ra. Basil Kuriachen et al [10] used two level full factorial techniques for modelling and predicting the surface roughness in WEDM of titanium (Ti-6Al-4V) alloy. The predicted values of surface roughness by the mathematical model were compared with the experimental values. The pulse on time , dielectric pressure, the interaction of voltage and pulse on time are significant parameters which affect the surface roughness. Minimum surface roughness can be obtained by adopting a low value of pulse on time (20 µs) and a high value of dielectric pressure (15 kgf/cm2). Peter Pinke et al. [11]observed the influence of the solution treatment at 1050°C, 950°C and 800°C with water or air cooling followed by aging treatment at 550°C was investigated on the specimens from Ti-6Al-4V model titanium alloy. After the treatments 1050°C water and 950°C water α′ martensite structure was created, in the other cases a lamellar structure of α + β phases was formed. The results obtained from experimental heat treatment of casted Ti-6Al-4V model alloy show that an α′ martensitic structure is formed after water cooling from the solution treatment at 1050 °C. After the water cooling from 800°C only an α phase lamellar structure was created in the untransformed β phase. Marte α′ structure did not appear. After water cooling from 950 °C α′ martensite structure with primary α phase was formed. Air cooling from each solution temperature lead to lamellar structure of α+β phases. The character of the formed microstructures has not changed basically after the aging treatment at 550°C. The highest growth of hardness compared with the initial hardness was detected after the heat treatment at 1050 °C/1h/water + 550 °C/4h.

After detailed study of above mentioned different research papers it has been concluded that hardness of Ti-6Al-4V is increased by increasing the temperature up to 1100°C followed by water quenching as compared to other quenching methods. It is also observed that machining of heat treated hardened Ti-6Al-4V on WEDM was not performed by many researchers. So machining of heat treated hardened Ti-6Al-4V on WEDM is experimented in this research work .The process parameters of WEDM that were frequently used and found to be more influential than the rest were Pulse-On Time, Pulse-Off Time, Peak Current, Wire Feed Rate, Wire tension and Servo Voltage . Hence, these process parameters were studied in this research work.

III. Experimental procedure and analysis

Cold-rolled cylindrical plate of Ti-6Al-4V with a size of 40 mm diameter and 6 mm thickness was used in this study. The chemical compositions of Ti-6Al-4V are listed in Table 1.

Table 1: Chemical compositions of Ti-6Al-4V (mass%)

Element	Al	Fe	V	C	Ti
%	5.75	0.28	3.9	0.08	remaining

Hardness value of Ti-6Al-4V before heat treatment was checked using Rockwell hardness tester and mean was taken into account, which is 28 HRC. The samples were heat treated in muffle furnace at 1100ºC .All the samples were kept in the furnace for 1 hour. During heat treatment, the temperature was gradually increased from room temperature; about 25°C/minute to final temperature 1100ºC hold for 1 hour of time. Then heat treated specimens were quenched in water one by one. After heat treatment of specimens at 1100°C the hardness was checked on random samples on Rockwell hardness testing machine.

Table 2: Measurement table of hardness

Temperature (^{0}C)	Time (hr)	Hardness 1 (HRC)	Hardness 2 (HRC)	Hardness 3(HRC)	Mean (HRC)
1100	1	38.7	39.3	38.6	39.20

Heat treated Ti-6Al-4V was used as work-piece material. It was essential to select proper machining parameters for effective machining of Heat treated Ti-6Al-4V. The heat treated work-piece samples Ti-6Al-4V was used for machining study on CNC Wire Electrical Discharge Machine model Electronica (ELPLUS 40A DLX)

Figure 2: CNC WIRE EDM Setup for machining

Experiments were conducted based on Taguchi's method and as per $L_{25}(5^6)$ orthogonal array while considering six controllable factors (i.e. parameters), with five levels each. The values taken by factors are termed as levels. The factors and their levels are detailed in the Table 3.

Table 3: Cutting Parameters and Their Levels to be used in WEDM.

S.No	Input Parameters	Levels				
		1	2	3	4	5
1	Pulse On- Time (TON) µs	112	116	120	124	128
2	Pulse Off Time (TOFF) µs	51	54	57	60	63
3	Peak Current (IP) A	70	110	150	190	230
4	Wire tension Kg-f	4	6	8	10	12
5	Servo Voltage Volts	10	30	50	70	90
6	Wire Feed rate mm/min	6	7	8	9	10

After machining of all specimens material removal rate is calculated by the following relation

MRR- Volume removed (mm³)/ time (minutes)

The kerf has been measured using the profile projector as the sum of the wire diameter and twice wire workpiece gap. The kerf is so small that it can't be measured with scale and caliper so profile projector is used which projects the image of workpiece on the screen so that it can be easily measured.

IV. Results and discussion

After all the experimentations and measurements, it is required to study the effect of different machining parameters of WEDM for machining of heat treated Ti-6Al-4V. The metal removal rate , Kerf width has been measured for each experiment to study the effects of pulse on time, pulse off time, peak current, Wire feed rate , wire tension and servo voltage on performance during machining.

Table 4: Experimental result for MRR,KW

RUN	T-On µs	T- Off µs	IP Amps	WT Kg-f	SV Volts	W F m/ min	Volume (5x5x6) = 150 mm³	Cutting time minutes	MRR mm³/ min	K W (mm)
1	110	51	70	4	10	6	150	9.18	16.339	0.275
2	110	54	110	6	30	7	150	12.11	12.386	0.286
3	110	57	150	8	50	8	150	19.17	7.824	0.282
4	110	60	190	10	70	9	150	33.11	4.530	0.264
5	110	63	230	12	90	10	150	50.19	2.988	0.290
6	115	51	110	8	70	10	150	15.34	9.778	0.278
7	115	54	150	10	90	6	150	33.11	4.530	0.289
8	115	57	190	12	10	7	150	5.50	27.272	0.265
9	115	60	230	4	30	8	150	7.36	20.380	0.300
10	115	63	70	6	50	9	150	24.08	6.229	0.266
11	120	51	150	12	30	9	150	4.07	36.855	0.285
12	120	54	190	4	50	10	150	5.21	28.790	0.261
13	120	57	230	6	70	6	150	7.43	20.188	0.305
14	120	60	70	8	90	7	150	38.34	3.912	0.277
15	120	63	110	10	10	8	150	5.25	28.571	0.267
16	125	51	190	6	90	8	150	8.58	17.482	0.285
17	125	54	230	8	10	9	150	4.16	36.057	0.280
18	125	57	70	10	30	10	150	8.44	17.772	0.275
19	125	60	110	12	50	6	150	7.18	20.891	0.276
20	125	63	150	4	70	7	150	9.53	15.739	0.312
21	130	51	230	10	50	7	150	2.54	59.055	0.305
22	130	54	70	12	70	8	150	16.37	9.163	0.297
23	130	57	110	4	90	9	150	18.30	8.196	0.312
24	130	60	150	6	10	10	150	5.17	29.013	0.262
25	130	63	190	8	30	6	150	3.31	45.317	0.293

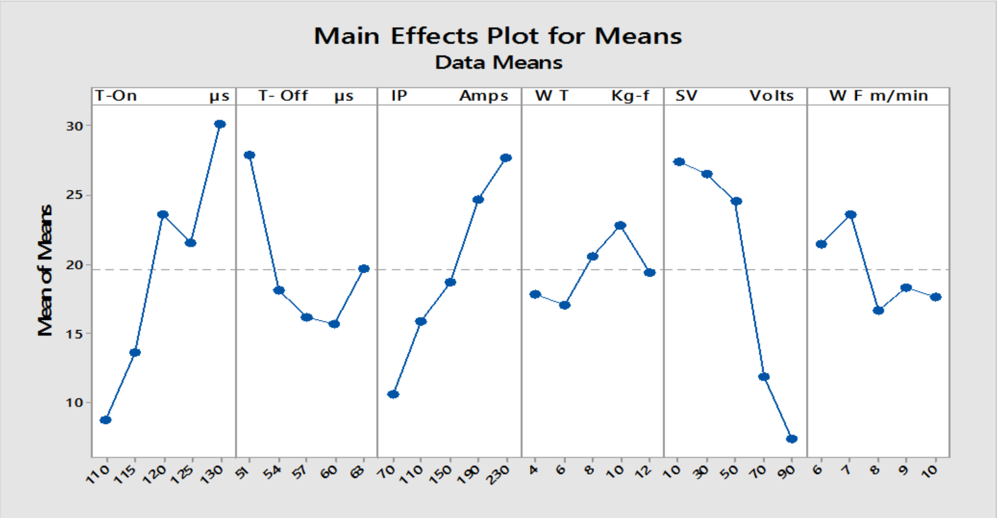

Figure 2: Response graph for means (MRR)

The Experimental results show the effect of six process parameters on material removal rate. Fig-2 shows the effect of material removal rate for the pulse on, pulse off, peak Current, wire tension and Servo Voltage by response graph for means (Ra). From this Fig, it was observed that the MRR increased when the pulse on time was increased due to number of discharges within a given period of time increase.

Table 5: Response Table for Means(MRR)

Level	T-on	T-Off	PC	WT	SV	WF
1	8.813	27.902	10.683	17.889	27.450	21.453
2	13.638	18.185	15.964	17.060	26.542	23.673
3	23.663	16.250	18.792	20.578	24.558	16.684
4	21.588	15.745	24.678	22.892	11.880	18.373
5	30.149	19.769	27.734	19.434	7.422	17.668
Delta	21.335	12.157	17.051	5.832	20.029	6.989
Rank	1	4	3	6	2	5

Table 5 shows the response table for means ranking of WEDM Parameters for highest material removal rate. It shows that the pulse on time has the highest effect on surface roughness of machined surfaces. The IP (peak current) has lowest effect on surface roughness of machined surface by WEDM

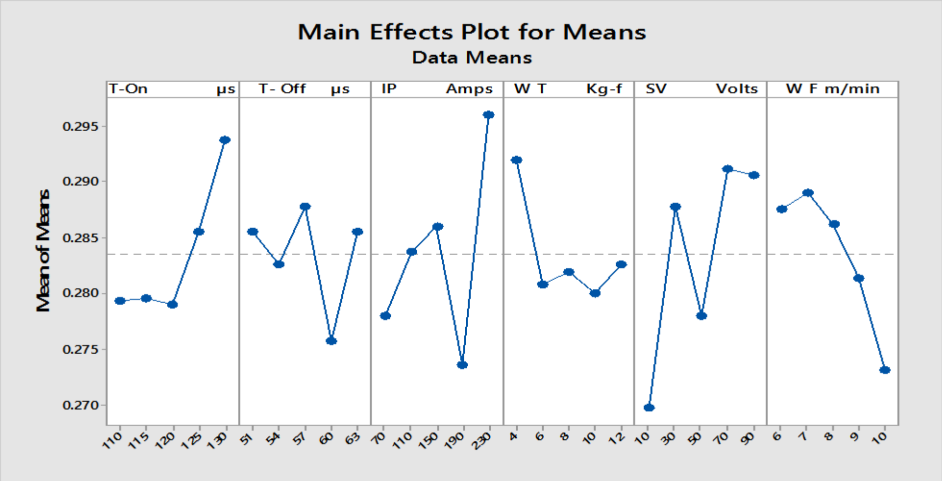

Figure 3: Response graph for means (KW)

The Experimental results show the effect of six process parameters on kerf width. Fig 3 shows the effect of material removal rate for the pulse on, pulse off, peak Current, wire tension and Servo Voltage by response graph for means (KW). From this Fig, it was observed that with increase in pulse on time the kerf width increases.

Table 6: Response table for means (KW)

Level	T-On	T-Off	IP	WT	SV	WF
1	0.2794	0.2856	0.2780	0.2920	0.2698	0.2876
2	0.2796	0.2826	0.2838	0.2808	0.2878	0.2890
3	0.2790	0.2878	0.2860	0.2820	0.2780	0.2862
4	0.2856	0.2758	0.2736	0.2800	0.2912	0.2814
5	0.2938	0.2856	0.2960	0.2826	0.2906	0.2732
Delta	0.0148	0.0120	0.0224	0.0120	0.0214	0.0158
Rank	4	6	1	5	2	3

Table 6 shows the response table for means ranking of WEDM Parameters for smaller kerf width. It shows that the IP has the highest effect on Kerf width of heat treated Ti-6Al-4V machined by WEDM. The Pulse Off has lowest effect on Kerf width of heat treated Ti-6Al-4V machined by WEDM

V. Microstructure investigation

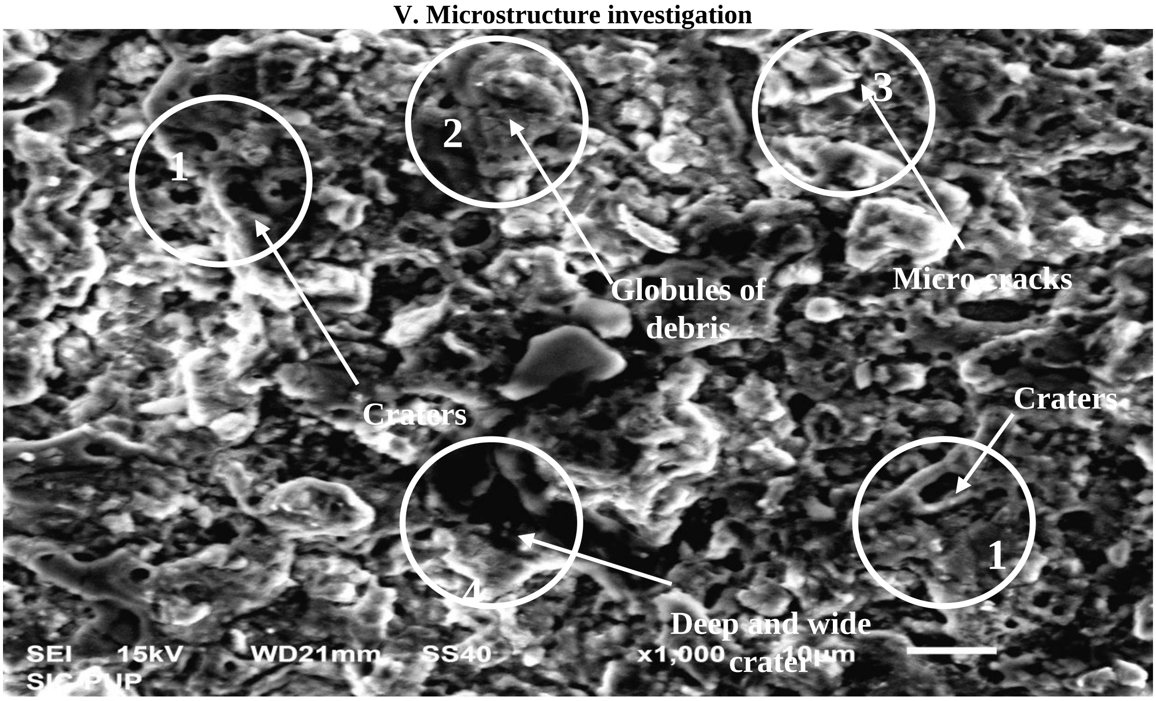

Figure 4: SEM micrographs (1000x): Exp. No. 5, at T-on = 110 μs, T-off=63μs, IP = 230 A, SV = 90V, WF= 10 m/min, WT= 12 Kg-f.

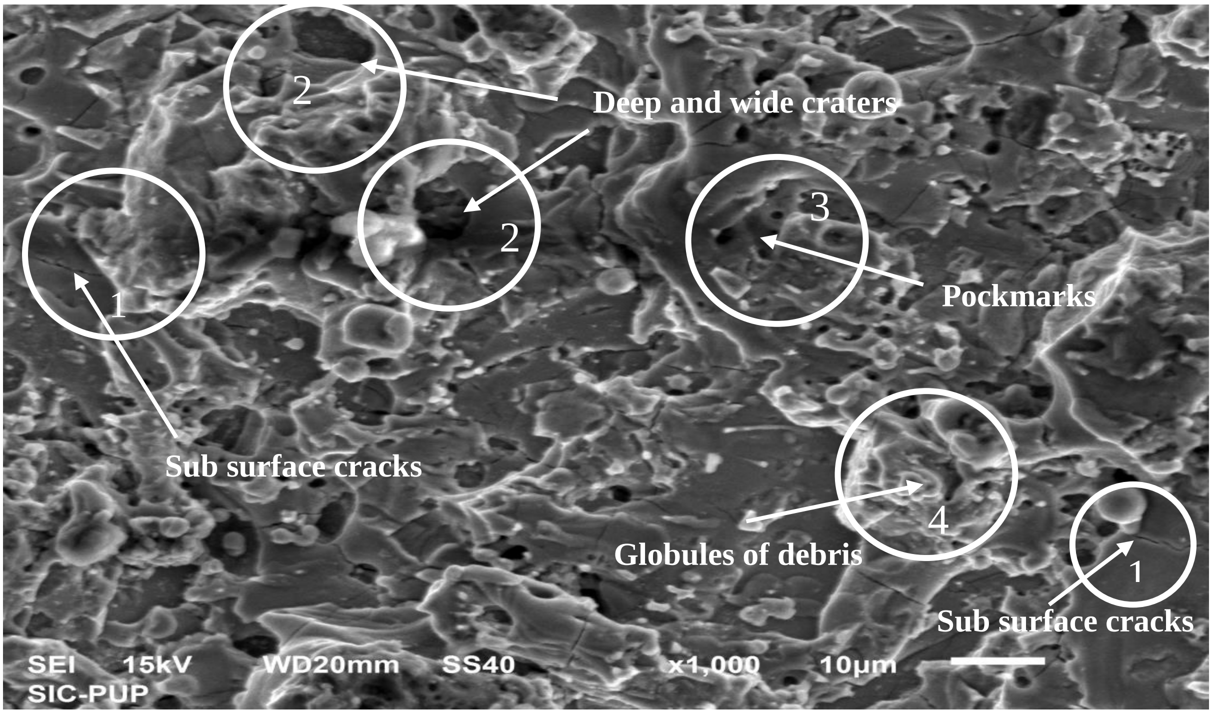

Figure 5: SEM micrographs (1000x): Exp. No 21. , at T-on = 130 μs, T-off=51μs, IP = 230 A, SV = 50V, WF= 7m/min, WT= 10Kg-f.

After WEDM operations, the machined specimens were examined using scanning electron microscope (SEM). A SEM (JEOL, Tokyo, Japan, model JSM-6610LV) analysis of machined surfaces of pure titanium has major micro structural changes after WEDM. Figures show the SEM image of machined surface with lowest and highest material removal rate. In these figures, the wire electrode was oriented vertically, and the table fed from left to right. The surface topography presented in figure 1 revealed that surface maybe caused by an uneven fusing structure, globules of debris (marked as 2), craters (marked as 1), micro cracks (marked as 3), deep and wide crater is (marked as 4). Figure 2 show the micro graph of machined surface with high material removal rate which shows that higher current equate to more thermal energy in the spark thus vaporizing and melting more of the workpiece material. This results in deep and wide craters (marked as 2) left in the surface of the workpiece. It should be noted that the sizes of the craters is effected by the amount of current that is allowed to pass through each of the sparks. The figure also reveals the globules of debris (marked as 4), pockmarks (marked as 3), Sub surface cracks (marked as 1) formation was usually associated with the development of high thermal stresses which exceeding the fracture strength, as well as with plastic deformation. In general, the density of cracks increases and more pronounces as the peak current and pulse duration was raised.

VI. Conclusion

The following conclusions are drawn on the basis of the experimental results after machining of Ti-6Al-4V by utilizing the Wire Electrical Discharge Machine (WEDM) and thereafter holding discussion and analysis on the investigated results.

1. The highest metal removal rate of 59.055 mm^3/min is noted at Pulse-ON Time 130 μs, Peak Current 230 A, Pulse OFF Time 51μs, Wire tension 10 Kg-f, Servo voltage 50V and Wire Feed Rate of 7m/min.
2. The Servo voltage has rank 1, so it is the most dominating for MRR of all the parameters . Wire Tension has rank 6, which means it is the least dominating for MRR among all the parameters.
3. The minimum Kerf Width of 0.261mm is noted at Pulse-ON Time 120 μs, Peak Current 190A, Pulse OFF Time 54 μs, Wire tension 4 Kg-f, Servo voltage 50V and Wire Feed Rate of 10m/min.
4. The Peak Current (IP) has rank 1, so it is the most dominating for Kerf Width of all the parameters. Wire Tension has rank 6, which means it is the least dominating among all the parameters of Kerf width.
5. For maximum material removal rate of heat treated Ti-6Al-4V, the optimal parametric combination is Pulse-ON Time 130 μs, Peak Current 230 A, Pulse OFF Time 51μs, Wire tension 10 Kg-f, Servo voltage 50V and Wire Feed Rate of 7m/min.
6. For minimum Kerf width, the optimal parametric combination is Pulse-ON Time 120 μs, Peak Current 190A, Pulse OFF Time 54 μs, Wire tension 4 Kg-f, Servo voltage 50V and Wire Feed Rate of 10m/min.

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