International Journal of Research in Engineering and Innovation (IJREI)
journal home page: http://www.ijrei.com
ISSN (Online): 2456-6934

Development of surface properties on Ti6Al4V by electric discharge machining

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Abstract

The purpose of this work is to study the effect of various process parameters of EDM on the surface roughness of Ti6Al4V.The input process parameters chosen were peak current, pulse on time, pulse off time and the response parameter was surface roughness. Each input process parameter was set at three different levels. The most significant process parameters in contributing surface roughness have been optimized by using Taguchi. All other parameters of EDM are kept constant during experiments.
In this work the surface roughness was found 0.947µm at I= 3 Amp, T_{on} =50 µs, and T_{off} =200µs, whereas surface roughness was drop by 6% i.e. 0.890µm when pulse off time was increased by 100µs at same pulse on time and current. Further with the changed value, I= 4.5 Amp, T_{on} =50 µs, T_{off} =100µs, surface roughness obtained is R_a= 0.815µm, but with the increment in the value of pulse off time T_{off} = 200µs, again there is a 12.3% drop in the surface roughness value which is equal to 0.715µm. The effect of peak current, pulse on time, and pulse off time on the surface topography was investigated by SEM analysis.

Keywords: Thermodynamic Analysis, Energy-Exergy Analysis, Entropy Generation principle, Irreversibility Analysis

1. Introduction

To meet the ever increasing demand of modern days technology, there is requirement of materials and the process which can satisfy various specific properties such as high specific strength, good wear resistance and high strength to weight ratio that too at low cost. There are two main practical problems that engineers faces in obtaining such desired properties. First, to determine the values of the process' parameters that will yield the desired product quality (meet technical specifications) and the second is to maximize manufacturing system performance using the available resources. Researchers are very interested in developing surface modification technology that can be easily operated and that to at low cost to improve the mechanical properties of machined surface. Thermal, mechanical and chemical effects resulting from manufacturing processes initiate surface modification. It has to be considered that in terms of machining operations all processes which produce a single surface affect the surface condition. The resulting surface integrity is an interaction of all surface manufacturing processes which produced the surface. The quality of an EDMed surface is generally remarked as surface integrity which is characterized by major alterations such as surface roughness, white layer (recast layer), formation of surface cracks, metallurgical changes on surface and subsurface regions and hardness distribution. Many input parameters are effective on surface integrity of EDMed surface such as pulse current, pulse on time, open circuit voltage, electrode polarity, and tool Electrode and workpiece materials.

1.1 Surface Roughness

Surface roughness is a widely used index of product quality and in most cases a technical requirement for mechanical products. Achieving the desired surface quality is of great importance for the functional behavior of a part. On the other hand, the process dependent nature of the surface roughness formation mechanism along with the numerous uncontrollable factors that influence pertinent phenomena make almost impossible a straightforward solution. The most common strategy involves the selection of conservative

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process parameters, which neither guarantees the achievement of the desired surface finish nor attains high metal removal rate.

Surface roughness refers to deviation from the nominal surface of the third up to sixth order. Order of deviation is defined in international standards [1]. First- and second-order deviations refer to form, i.e. flatness, circularity, etc. and to waviness, respectively, and are due to machine tool errors, deformation of the workpiece, erroneous setups and clamping, vibration and workpiece material in homogeneities. Third- and fourth-order deviations refer to periodic grooves, and to cracks and dilapidations, which are connected to the shape and condition of the cutting edges, chip formation and process kinematics. Fifth- and sixth-order deviations refer to workpiece material structure, which is connected to physical–chemical mechanisms acting on a grain and lattice scale (Slip, diffusion, oxidation, residual stress, etc.). Different order deviations are superimposed and form the surface roughness profile, see Fig. 1.

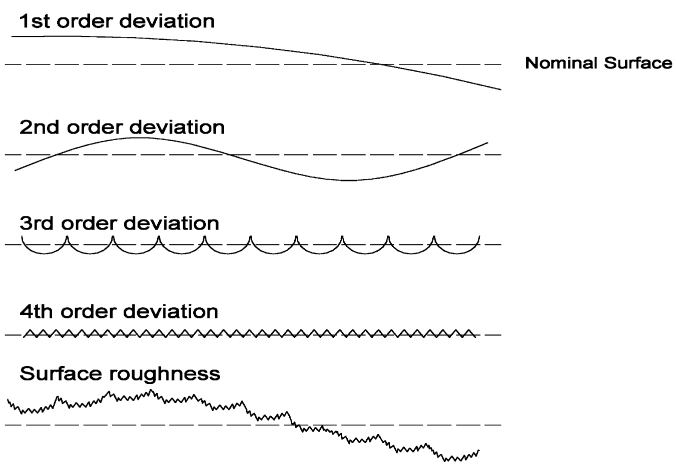


Figure 1: Surface form deviations [1]

1.2 Literature Review

The surface modification includes dry and wet chemical methods to improve various material surface properties

The modifying surface of titanium by EDM using urea solution into distilled water and distilled water with copper electrode. In the experiments, machining parameters such as the dielectric type, peak current and pulse duration were changed to explore their effects on machining performance parameters such as MRR, electrode wear rate, and surface roughness. It was investigated that by adding urea into the dielectric, MRR and EWR increases with increase in peak current, surface roughness deteriorated with an increase in peak current and the nitrogen element decomposed from the dielectric that contains urea, migrated to the work piece, forming a TiN hard layer, resulting in good wear resistance of the machined surface after EDM [2].

Dental casting pattern rings of Au-Ag alloy (stabilor), Co-Cr(Okta C) and Ti-cpTi alloy(Biotan) was prepared. These casting rings were subjected to conventional ground and polishing process and EDM process. These ground and polished surfaces and EDM generated surfaces were examined through SEM/X-ray EDS to analyze the surface morphology and the elemental composition. It was found that the EDM surface showed a significant increase in C due to the decomposition of the dielectric fluid during spark erosion. Moreover, a significant Cu uptake was noted on these surfaces from the decomposition of the copper electrodes used for EDM. It also had been observed that all alloys developed a recast layer varying from 2µm for Au-Ag to 10µm for Co-Cr alloy [3].

A review on current trends in electrical discharge machining was presented. The review presented various machining techniques presently used in EDM such as ultrasonic vibration, dry EDM machining, EDM with powder additives, EDM in water and modeling techniques. In this paper electrode wear ratio, MRR and tool wear in various type off EDM processes are studied. Various modeling techniques such as dimensional analysis, mathematical modeling, and artificial neural network implemented to analyze the performance of the EDM. Review about the micro EDM and wire cut EDM also been made [4]. The effect of electric discharge machining process parameters on surface integrity of Ti6Al4V using different electrode material of copper, graphite and aluminum was studied. They found out that the average white layer thickness increases with increase in EDM process parameters. Electrode material has no effect on the white layer thickness Surface cracking can be eliminated after 6A and 3A pulse current for aluminum and graphite electrode [5]. Effect of electrical discharge machining process on the formation of nanoporous biocompatible layer on titanium was investigated. An ASTM F67 grade IV Ti was EDMed using distilled water with a copper electrode. It was found that electrical discharging not only generates a nanostructural recast layer but also converts the alloy surface into a nanostructured oxide surface, which increases the alloy biocompatibility [6]. The feasibility of EDM for processing the bio-ceramics such as ZrO_2 and Al_2O_3 using an assisted conductive material named adherent copper foil on ceramic surfaces to induce a series of electrical discharge between tool electrode and workpiece in the initial stage of EDM process. The experiment results shows that the MRR of ceramic material was promoted, since the effect of thermal spalling was enhanced at larger discharge energy [7].

Glass shaped samples for fatigue tests and flat samples for roughness measurement for processing by EDM with graphite electrodes and using hydrocarbon oil as dielectric liquid. The benchmark samples for fatigue tests were electrolytically polished at temperature -20^{o}C.m. It was observed that EDM process induced sufficient surface roughness to enhance bone in growth. Moreover, favorable chemical changes of the surface were observed [8]. Electro-spark alloying treatment on the titanium alloy surface using a graphite electrode, in air, under nitrogen gas and in silicone oil was proposed. In the study a commercial high purity graphite rod with a diameter of 10 mm was used as anode electrode. Silicone oil and nitrogen gas were used as protection media in order to reduce and ultimately avoid the formation of cracks [9]. Surface integrity aspects of Ti-6Al-4V specimen using grinding and wire EDM process was compared. Both the specimens are visually inspected and found that the ground surface is shinier than eroded surface and also ground surface have lower surface roughness than the eroded one obtained from EDM. The fatigue life tests are performed on both the specimens and result obtained shows that the ground specimen have an increased fatigue life [10]. The effects of EDM parameters on surface integrity, MRR and TWR in machining of Ti6Al4V.Three variables input machining parameters pulse current, pulse on time, and open circuit voltage were changed in EDM process. Output characteristics such as material removal rate, tool wear ratio and different aspects of surface integrity such as topography of machined surface, crack formation, white layer thickness and micro-hardness were investigated. They found that MRR increases with increase in pulse on time, TWR also increases with pulse on time but in the higher range of pulse on time, effect on TWR is minimal. Also by increasing the pulse current, micro holes and pits, crack dimensions and surface inequalities are increased, by increasing the pulse on time, density of micro holes, pits and surface cracks is increased [11].

Two group of specimens that were prepared from Co-Cr (okta-C0 and a grade II cpTi (Biotan) alloy respectively. One group specimens of both the alloy were subjected to EDM with copper electrodes operated at 90V voltage and 0.5-1.5 ampere current and second group specimens of both alloys were subjected to conventionally finishing process. In all stages dielectric fluid used was kerosene It had been found that EDM procedure decreases the corrosion resistance of both the alloys tested, increasing the risk of possible adverse biological reactions [12].

Experiments using EDM to generate surface at three different pulse durations, which varied from 10μs to 60μs. The positive electrode was made of grade II pure titanium, whereas the negative electrode was a pretreated- Ti64 specimen, with distilled water as dielectric solvent. The surface topographies of each specimen were qualitatively characterized using SEM, and X-ray photoelectron spectroscopy was used to analyze the depth profiles of the elements. Comparison of treated and untreated surface had been done and found that the without surface have relatively smoother surface with regular polishing grooves, while EDM treated surface had volcano- like configuration including globules of debris and a low density of nanoscale pits at low pulse duration and larger and deeper pores at higher pulse duration still at nanoscale level. This demonstrated that EDM produced the microscale roughness but also created the nanoporous TiO_2 layers, which helps in early osseo integration [13].

A surface modification on Ti-6Al-4V with combine technique of EDM, acid etching and shot peening in order to create a superimposed topography that may provide more suitable surface for osteoblast proliferation. It had been investigated that surface treatment consisting of consequent use of electric discharge machining and acid etching with or without shot peening creates a superimposed surface topography that enhances proliferation of osteoblast-like cells that is well applicable in orthopeadics for manufacturing implant material for total endo prostheses [14]. A comparative study on conventional machined surface and EDMed surface of CpTi surfaces to assess the effect of surface roughness parameters, the hardness, and the elemental and molecular alteration induced on the surface. They found out that the EDM alters the surface properties of cast CpTi including morphology, surface roughness parameters, elemental and molecular composition, and hardness. These alterations affect the clinical efficacy [15].

The influence of process parameters including peak current, pulse on time, pulse off time, flow rate, and concentration of powder particles on MRR, TWR and surface roughness using powder mixed near dry electrical discharge machining. In this high speed steel and W18Cr4V is used as workpiece and copper tubular as electrode [16].

The effects of parameters on EDM characteristics such as material removal rate, and tool wear rate on Ti6Al4V utilizing copper tungsten as negative electrode investigated. Design of experiments method and response surface methodology techniques are adopted to attain the objectives. 2-D and 3-D contour plots are generated to study the effect of peak current and pulse off time on MRR and TWR. It was found that high discharge current causes more electrode wear. Low pulse off time permit low tool wear and the material removal rate is greatly influenced by peak current and pulse on time. They found out that the material removal rate is greatly influenced by peak current and pulse on time. The MRR increases with increase in pulse current and pulse on time and constant decrease as pulse off time increases. Long pulse off time permits low tool wear [17].

Effect of electrical discharging on formation of nanoporous biocompatible layer on Ti6Al4V alloy was investigated. A surgical grade Ti6Al4V(ASTM F136-92) specimen was used as negative electrode and grade- II Ti was made positive electrode, with distilled water as dielectric fluid. It was found that the cytocompatibility of the Ti6Al4V specimens improves when oxygen penetrates into the specimen and results in a thick thickness of antite- TiO_2 layer near the surface, which roughened the EDM treated surface on a microscale. An increase in adherence, proliferation, and differentiation of cells was noticed indicating biological capability of Ti64 specimens [18].

The effect of wire EDM process on the fatigue life of Ti-6Al-2Sn-4Zr-6Mo alloy was studied. The specimens were subjected to WEDM and milling process and fatigue life of both the specimen were carried out. They found out that the fatigue run-out for WEDM specimens were recorded at an endurance limit to ultimate tensile strength ratio of 0.59 and for milling the ratio was 0.62 [19].

An innovative surface modification of Ti6Al4V alloy to study osteoblast proliferation and fatigue performance was performed. They used graphite electrode and hydrocarbon oil as a dielectric liquid for EDM process. Two different shot peening process were applied, in the first process ceramic balls (ZrO_2 and SiO_2 mixture) of 350μm diameter and in second process ceramic ball of 125-250μm diameter was used. Hour glass samples were prepared for fatigue tests. It was found that shot- peening followed by EDM reduces the overall surface roughness, fatigue strength of EDM treated alloy is significantly improved by shot- peening only when sufficiently small shots and high Almen intensity is applied [20]. Reference fatigue behavior was obtained from specimens produced with conventional milling process. Specimen's surface produced by EDM are grouped and given post- processing techniques, including mechanical polishing, electro polishing, chemical milling, shot peening and laser peening. It had been investigated that measured fatigue behaviors of all specimens produced by EDM demonstrated diminished performance relative to specimens fabricated with conventional milling techniques. Also effects of post processing techniques were observed fatigue strengths exhibited by bead-blasted specimens were superior to those of specimens subjected to all other treatments [21]. The properties studied are improving attachment to biological cells, corrosion resistance, and weldability, altering the bioactivity, inhabiting bacterial growth, improving the compressive strength and hardness, and improved surface hardness. They found out that electron beam melting can enhance properties of cell attachment of Ti6Al4V scaffold, coarse particle blasting and laser gas nitriding improve the corrosion resistance, altering the voltage applied for the treatment of the alloy can inhibit bacterial growth [22]. A β-Ti-based implant subjected to powder mixed electric discharge machining for surface modification was investigated. They use a pure Ti (Cp- Ti) alloy as anode and a β- Ti alloy (workpiece) as cathode, and silicon powder was mixed in the dielectric fluid. It was experimentally observed that a novel biomimetic nano porous surface, featuring a mixture of bio ceramic oxides and carbides phases, was successfully generated on β-Ti surface by PMEDM for orthopedic applications. The bio ceramic oxides conferred bioactivity and improvement in biocompatibility of the implant surface. The PMEDM prepared surface nano porous surface exhibits higher level of cell attachments, distribution, and proliferation when compared with untreated surface [23].

Copper tungsten as an electrode to machined tungsten carbide for experimentation was used. They found out that to obtain good surface finish low value of peak current, pulse off time and voltage should be used. Also for tungsten carbide to obtain high metal removal rate, high value of peak current and voltage should be used [24].

An optimization model using response surface methodology and investigate effect of peak current, pulse on time and pulse off time, on electrical discharge machining performance was developed. The material under investigation is Ti-6Al-4V with copper electrode with negative polarity. They observed that the metal removal rate increases with an increase in peak current and pulse on time and decreases with an increase in pulse off time. Analysis of variance (ANOVA) has been performed for the validity test of fit [25]. The influence of input parameters on the electrical discharge machining process was investigated. They studied the machining features, metal removal rate, tool wear ratio, surface roughness, thickness of the white layer and depth of heat affected zone on AISI H13 tool steel workpiece. They found that an increase in pulse on time will increase metal removal rate, surface roughness, white layer thickness and depth of heat affected zone [26]. The influence of process parameters of electric discharge machining i.e. pulse on time(T_{on}),peak current(I_p),duty factor(t),gap voltage(V_g) on electrode wear rate, material removal rate and radial over cut using copper electrode was observed. The workpiece material is AISI D3 steel. They found out that peak current made much influence on material removal rate, electrode wear rate and radial overcut, while other factors pulse on time, duty factor and gap voltage has little effect on these parameters [27].

An optimizing of input parameters, pulse on time (T_{on}), pulse of time (T_{off}), and current (I) for machining titanium alloy Ti-6Al-4V of copper electrode, using Taguchi and ANOVA was investigated. They observed that current had a greater influence on surface roughness followed by pulse off time. Pulse on time had little impact on surface roughness [28].

Material Removal Rate (MRR), Tool Wear Rate (TWR) and Surface Roughness (SR) using different electrode material viz, Aluminum, copper and brass was measured. The workpiece material is stainless steel 304.They observed that for high discharge current, copper electrode show highest metal removal rate, while brass electrode gave a good surface finish and normal metal removal rate [29].

Precision and passive fitting has been unpredictable with conventional methods of casting as well as for corrective techniques (i.e recasting, soldering, welding) for meso- and super-structure fabrication was found. Alternative to conventional techniques, electro discharge machining (EDM) is an advanced method introduced to dental technology to improve the passive fitting of implant retained overdentures. In this technique material is removed by melting and vaporization in single sparks. The last is the reason why EDM is commonly known in dental literature as "spark erosion" [30]. The mechanical properties of aluminum, nylon, GFRP, aluminum-GFRP composite & aluminum-nylon composite were found by using experimental method, The deflection of aluminum composite beams is less than that of pure material beams, the natural frequencies of pure materials (GFRP & Nylon) are larger than those of composite beams made by them if nylon is taken as synthetic fiber with Al, but if GFRP is taken then its deflection is found to be increased when compared to pure GFRP. So, nylon suits good to make composite beam with Al as compared to other synthetic fibers like GFRP [31, 32]. The EDM recast layer can be beneficial providing increased abrasion resistance while in other cases is removed by successive surface treatments, such as hand polishing, etching or heat treatment was observed. The Cu uptake is readily explained from the decomposition of Cu electrodes, something which is also a common finding after the EDM procedure [33].

EDM features several disadvantages such as low surface roughness, low material removal rate, instability in machining conditions, high surface crack density, and generation of deep and wide craters was observed. As a result, different types of surface and sub-surfaces flaws are generated in the machined surface [34].

Trace amount of liquid-powder mixture is delivered into discharge gap by compressed air and discharge gap was found enlarged. The reduction of the volume of liquid phase in the dielectric medium and the enlargement of discharge gap which is mainly caused by the addition of powder particles could contribute to the improvement of discharge stability and the reduction of thermal load on the tool electrode. As a result, higher MRR can be obtained along with low TWR in PMND-EDM [35].

The ultimate tensile strength of the alloy improved as compared to LM 12, the solidifications temperature for Al-Alloy reduces and this is an important factor to consider which temperature the heat treatment not should exceed. When increase the silicon content then the melting point of aluminum alloy is decreases whereas fluidity was increases [36, 37]. Competitiveness of each EDM processing technology, many processing experiments are conducted by researchers to improve EDM processing properties. One purpose of these studies is to make clear the influence of process parameters on performance parameters. Then improve the machining properties of EDM processing technology by controlling process parameters. Influence of each processing parameter on performance parameters can be obtained based on single factor experiments and orthogonal design experiments [38].

Preliminary data for the elemental alterations of EDM-treated vs conventionally polished Ti surfaces, there is no information for the roughness, molecular structure, and mechanical properties of these surfaces. Therefore, the aim of this study was to comparatively evaluate the differences in surface roughness parameters, elemental composition, molecular structure, and hardness between conventionally polished and EDM-treated Ti surfaces. The null hypothesis tested was that EDM treated Ti surfaces demonstrate different surface properties from conventionally polished surfaces [39]. Welding parameter such as tool rotation, transverse speed and axial force have a significant effect on the amount of heat generated and strength of FSW joints. Microstructure evaluation of FSW joints clearly shows the formation of new fine grains and refinement of reinforcement particles in the weld zone with different amount of heat input by controlling the welding parameter [40-42]

2. Selection of Workpiece

Titanium is light in weight and has atomic weight of 22. It is silver-gray in color with low density, high corrosion resistance and high strength. Beside this titanium and its alloy have good electrical conductivity and thermal conductivity. The non-toxic nature and biocompatibility of Ti6Al4V is excellent, especially when its surface is in direct contact with the body tissue or bone [32].Ti6Al4V possess 960-970 MPa of ultimate strength and young modulus of 110 GPa which is almost closer to that of bone (10-30 GPa) compared to stainless steel (around 180 GPa) and Co- Cr alloys (around 210 GPa).The work piece material employed for the study was Ti6Al4V.

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

Ti-6Al-4V	Ti	Al	V	C	Fe	O	N	H
	89.46	6.08	4.02	0.02	0.22	0.18	0.18	0.0053

Table 2: Mechanical Properties of Ti-6Al-4V

Melting Point ^0C	UTS MPa	Y.S MPa	Impact-toughness (J)	Young's Modulus GPa	Tensile strength MPa	Density m^3
1660	832	745	34	110	10^3	4420

2.1 Selection of Electrode

Copper was selected as an electrode material because of its high electrical conductivity and thermal conductivity. Table 3 shows the physical properties of copper electrode used for the experimental work

Table 3: Physical properties of copper electrode [36]

Electrode Material	Thermal Conductivity	Melting point	Boiling Temperature	Specific heat	Specific gravity at 20ºC	Coefficient of thermal expansion	Length of Workpiece	Diameter of Workpiece
Copper	380.7 W/m-K	1083 ºC	2595ºC	0.092 cal/g. ºC	8.9 g/cm^3	17x 10^{-6}(1/ºC)]	50mm	10 mm

Fig. 2 Showed copper electrode used during machining of Ti-6Al-4V has been shown

Figure 2: Copper electrode

2.2 Experimental Setup

The EDM machine Tool craft was used for the experimentation. Polarity of the electrode was kept as positive and polarity of work piece was negative. Table 4 gives description of experimental setup used for experiment

Table 4: Description of Experimental setup used for experiment

Workpiece Material	Ti-6Al-4v
Length of workpiece	50 mm
Diameter of workpiece	10 mm
EDM used	G30 integrated spark generator type
Tool material	Copper
Measuring instrument	Profilometer, used for measuring surface roughness , R_a
Dielectric fluid	EDM-30 oil

A die sinking electrical discharge machine (Model: G30 integrated spark generator type, Make: Toolcraft (India) normally used in tool and die shop was chosen for experimental work. The EDM has an integrated type pulse generator. The specifications of EDM as well as pulse generator are given in Tables 5. The positive polarity was used in the present experimentation, because it is favorable for material transfer from workpiece to tool.

Table 5: Specifications of Electric Discharge Machining Tool craft NC machine

S. N	Machine Parameters	Values
1	Table size (L×B)	350 mm×200 mm
2	Tank size (L×B×H)	600 mm×370 mm×290mm
3	Dielectric fluid level over table (max)	200 mm
4	Quill stroke	200 mm
5	Maximum Electrode Weight	20 kg
6	Reservoir capacity	60 liter
7	Filtration capacity	10 micron
8	Supply voltage	415 V, 3 Phase, 50 Hz
9	Main voltage tolerance	± 10%
10	Machining current max	25 Amp
11	Open Gap voltage	60 ±5 voltage
12	Pulse Type	'Nal' pulse, Standard pulse
13	Pulse on-time	5 µsec to 1000 µsec
14	Pulse off-time	5 µsec to 1000 µsec

Fig. 3 shows the Electric Discharge Machine used to machine Ti6Al4V

Figure 3 : Electric Discharge Machine, Toolcraft NC machine

3. Results and Discussion

In this chapter discussion about the results obtained during experimentation and observations of electric discharge machining process using Ti-6Al-4V as workpiece material with copper electrode has been done. Taguchi's method and ANOVA is used to investigate the design parameters and to indicate which parameters are significantly affecting the output parameters. In the analysis the sum of squares and variance are calculated using MINITAB 17. An F-test value at 95% confidence level is used to decide the significant factors affecting the process.

3.1 Analysis for SR

The observed values of SR for each run are recorded in table 6. The analysis of results was computed by using software MINITAB

*Table 6: Orthogonal Array L27 (3*3) Response Table for Surface Roughness*

Sr. No.	I	T on	T off	Surface
1.	1.5	50	100	1.316
2.	1.5	50	200	1.116
3.	1.5	50	300	0.831
4.	1.5	75	100	1.2
5.	1.5	75	200	0.862
6.	1.5	75	300	0.918
7.	1.5	100	100	1.58
8.	1.5	100	200	0.94
9.	1.5	100	300	0.895
10.	3	50	100	1.118
11.	3	50	200	0.947
12.	3	50	300	0.89
13.	3	75	100	1.215
14.	3	75	200	1.171
15.	3	75	300	1.198
16.	3	100	100	1.085
17.	3	100	200	0.809
18.	3	100	300	1.212
19.	4.5	50	100	0.815
20.	4.5	50	200	0.715
21.	4.5	50	300	0.819
22.	4.5	75	100	1.32
23.	4.5	75	200	1.294
24.	4.5	75	300	0.901
25.	4.5	100	100	1.261
26.	4.5	100	200	1.073
27.	4.5	100	300	1.282

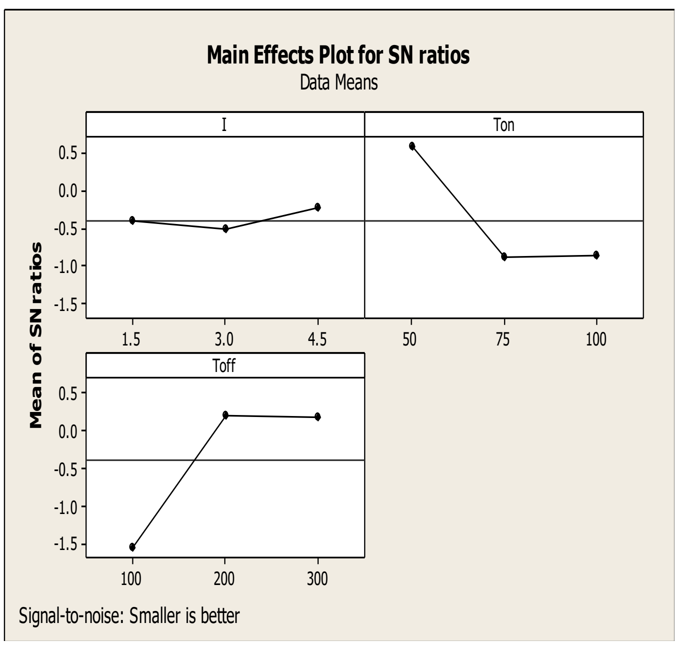


Figure 4: Main Effect Plots for SN ratio for Surface Roughness against Input Machining Parameters

The main effect plots for SN ratio surface roughness against input machining parameters are shown in fig. 4.

Table 7: Response Table for Signal to Noise Ratios (Smaller is better)

Level	I	T_{on}	T_{off}
1	-0.417	0.579	-1.5511
2	-0.517	-0.8808	0.2089
3	-0.2337	-0.866	0.1744
Delta	0.28333	1.4598	1.76
Rank	3	2	1

The main effect plots for means of surface roughness against input machining parameters are shown in table 7.

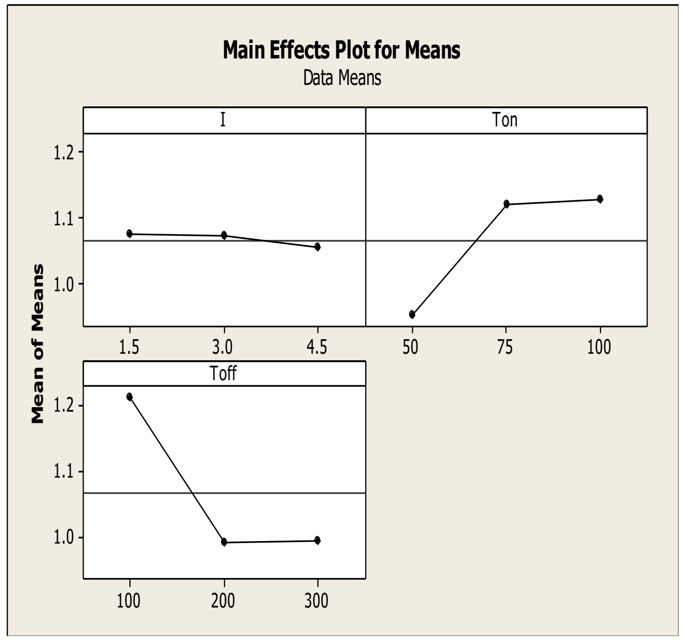


Figure 5: Main Effect Plots for means of Surface Roughness against Input Machining Parameters

Table 8: Response table for means

Level	I	T_{on}	T_{off}
1	1.0731	0.9519	1.2122
2	1.0717	1.1199	0.99919
3	1.0533	1.1263	0.994
Delta	0.0198	0.1744	0.2203
Rank	3	2	1

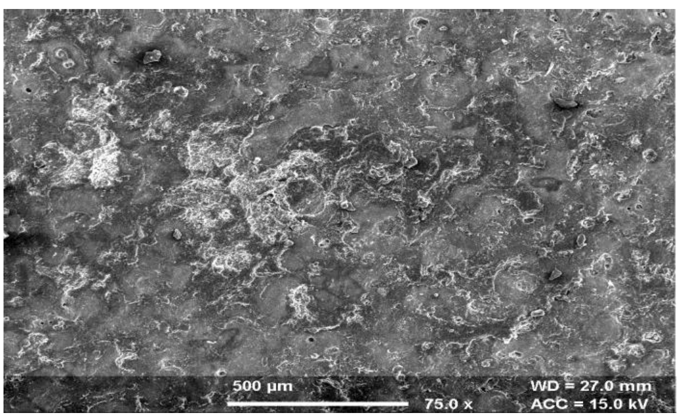
Table 9: Analysis of Variance for SR, using Adjusted SS for Tests

Source	DF	Seq SS	Adj. SS	Adj. MS	F	P
I	2	0.00219	0.00219	0.00109	0.03	0.97
T_{on}	2	0.17609	0.17609	0.08804	2.49	0.108
T_{off}	2	0.28852	0.28852	0.14426	4.09	0.33
Error	20	0.7061	0.7061	0.03531		
Total	26	1.1729				

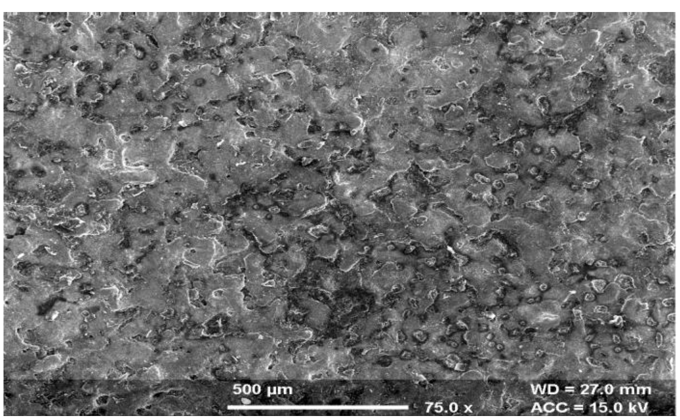
It had been observed from fig. 5 and table 8 that pulse- off time had major impact on surface roughness of machined surface of Ti6Al4V.
Comparing the F value in table 9 shows that pulse off time influences the surface roughness significantly at 95% confidence level. So, pulse off time is most significant factor of surface roughness.

3.2 SEM Observations of EDM Machined Surface

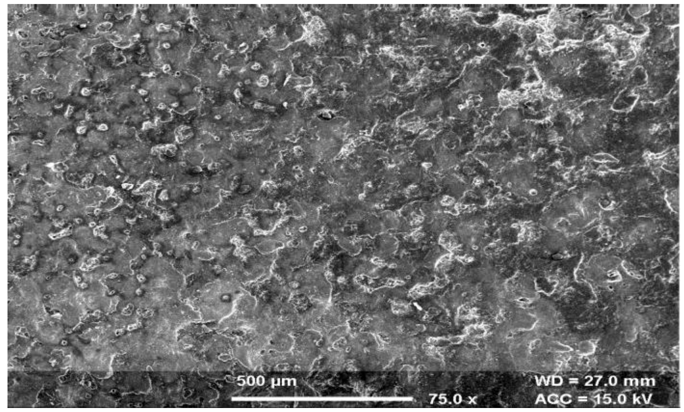
To investigate the effect of pulse off time, pulse on time and discharge current on machined surface topography, SEM images of three samples with75X magnification are presented in fig. 6.
It had been evident from the fig 6 (a) that when pulse on time is 100µs and pulse current is 3A, the micro holes and pits and abnormal surface inequalities resulting from arcs can be determine distinctly, resulting in rough surface.
Also, when the pulse current is increased to 4.5A and pulse off time is adjusted to 100µs, micro holes and pits and surface inequality are increased, this result is due to increase in discharge energy and impulsive force. With increase in pulse current leads to removal of more molten material during electric discharge and consequently produces larger and deeper craters and holes [10], which is clear in fig. 6 (b).



(a)



(b)



(c)

Figure 6: SEM observations of EDM machined surface of three samples with75X magnification, (a) Sample-1, (b) Sample-2, (c) Sample-3

As it is observed from the fig. 6 (c), with decrease in pulse on time to 50µs and increase in pulse off time to 200µs, the approximate density of micro holes and pits, surface cracks and irregularities is decreased. This result can be explained as, when pulse on time is decreased and pulse off time is increased, the amount of thermal energy transferred to the surface of sample is decreased. Resultantly, enhancing chance to molted material to solidify and giving time for proper cleaning of immersed debris and lead to stable condition of electric discharge. SEM image of fig. 6 (c) shows that the EDM machine surface had volcanic like globules of debris and a low density of nano scale pit holes.
It was found out that greater number of cells was formed on the smoother surface as compared to rough surface [21]. Also it had been observed and proved clinically by vivo study that nano-scale surface roughness considered to be more advantageous and favorable in the formation, adhesion, growth and differentiation of new bone cells [22].In this study the optimal setting of process parameters for optimal roughness is discharge current (4.5Amp), Pulse on time (75µs) and Pulse off time (300µs). Therefore it had been concluded that surface roughness at nano scale is influenced by high pulse off time.

3.3 Analysis of Recast Layer Thickness (RLT)

Recast layer is nothing but ridges of re-deposited molten metal, which depends on the values of peak current, pulse duration, pulse interval. The cross section SEM micrograph of the machined surface after EDM process is used to measure the RLT. The EDMed surface consists of high ridges of re-solidified molten metal which causes high RLT. The thickness of recast layers on the EDMed surface has been measured around 10-15 µm at a magnification of 2000x. It can be clearly seen that the re-solidified material has poor bonding and loosely connected, thus there is a risk of their loosening. These particles may cause considerable danger since they can penetrate between articulating parts of the joint and can damage them. The lower the recast layer thickness, lower will be the surface defects availability. The recast layer thickness reduced significantly. EDMed surface has thin recast layer. The thickness of recast layers on the EDMed surface has been measured around 5-10 µm.

Fig. 6 (c) shows the SEM micrographs of Ti implant surface at discharge current I= 4.5 A, pulse on time T_{on}= 75 µs, pulse off time T_{off}= 300µs. A very interesting surface features have been observed during analyzing the modified surface in SEM micrographs. The presence of micron, sub-microns and nano-scales surface porosity and foamy like structure has been identified on the top layer of the machined samples of the Ti alloy.

As reported in previous research studies, the nanoporous surface provides a biological environment for the growth of tissues around the implant and builds a strong biological interface and improved the implant stability. The fabrication of surface Nano-porosities led to the formation of a hyperphilic surface, which is expected to confer bioactivity and enhanced the biocompatibility of Ti implant and favorable for the Osseo integration or bone growth.

4. Conclusions

In the present work, the Ti-6Al-4V alloy was machined by electrical discharge machining process with different machining conditions. Summarizing the main features of the results, the following conclusions may be drawn:

- From response table 8 for signal to noise and response table for means, it is evident from the ranking that pulse off time has a greater influence on the surface roughness followed by pulse on time. Peak current has the least influence on roughness.
- From the table of ANOVA, it had been observed that pulse off time is the most significant factor for surface roughness.
- The increase in the peak current, there will be increase in the formation of micro holes and pits and surface inequality, resulting increase in surface roughness.
- With the increase in pulse off time, there will decrease in the density of pits, micro holes and surface cracks, which decreases roughness of the surface.

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