Optimization of Surface Roughness in Wire Electrical Discharge Machining of Titanium Alloy

Siva Prasad Arikatla[1], Dr K.Tamil Mannan[2], Dr Arkanti Krishnaiah[3]

Abstract - Wire Electrical Discharge Machining (WEDM) is extensively used for machining of complex shapes in the field of die and mould making, medical, aerospace and automobile industries for machining of too hard materials and to increase the machining productivity. Improper selection of WEDM process parameters setting can affect the machining efficiency and surface roughness due to arcing phenomenon that lead by discharge point of focus. Present study has been made to optimize the process parameters such as pulse on time, pulse off time, pulse current, servo voltage and wire tension during machining of Ti-6Al-4V titanium alloy by WEDM process using Response Surface Methodology (RSM). The analysis of variance (ANOVA) was carried out to study the effect of process parameters on process performance i.e. surface roughness. The mathematical models are also developed for surface roughness and validated with the experimental results. Further, the surface roughness of machined surface has been examined by using Scanning Electron Microscopy (SEM). The experimental results reveals that, as the pulse on time and input power increases, the surface roughness also increases. As and when the wire tension and servo voltage increases the surface roughness decreases and it improves the quality of machined surface. This paper highlights the importance of wire EDM process parameters on surface roughness and surface topography of wire electrical discharge machined surface of Titanium alloy work piece.

Index Terms - Wire EDM, ANOVA, Response Surface Methodology, Surface Roughness, SEM

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1. INTRODUCTION

TITANIUM alloys are hard metals which contain a mixture of titanium and other chemical elements. Ti6Al4V grade titanium alloy is the most popular titanium alloy and is used for a range of applications in the aerospace, marine, power generation and offshore industries. Titanium alloys have very high tensile strength, fatigue resistance, light in weight (highest strength-to-weight ratio), extraordinary corrosion resistance, toughness even at elevated temperatures and able to withstand high temperatures. However, the high cost of both raw materials and processing limit their use to military applications, air craft, spacecraft, medical devices, connecting rods on expensive sports cars and some premium sports equipment and consumer electronics. Auto manufacturers Porsche and Ferrari also use titanium alloys in engine components due to its durable properties in these high stress engine environments. Although "commercially pure" titanium has acceptable mechanical properties and has been used for orthopedic and dental implants, for most applications titanium is alloyed with small amounts of aluminum and vanadium.

This mixture has a solid solubility which varies dramatically with temperature, allowing it to undergo precipitation strengthening. This heat treatment process is carried out after the alloy has been worked into its final shape but before it is put to use, allowing much easier fabrication of a high-strength product. Yang, X, Liu, CR et al., studied the machining of titanium and its alloys [1], Kuriakose, Sh, Shanmugan MS et at., studied the characteristics of wire electro discharge machined Ti 6Al 4V surface [2] and Rahman.M.M et al., have done the modeling of machining parameters of Ti 6Al 4V for electric discharge machining using a neural network approach [3]. Titanium and its alloys are attractive and important materials in modern industry due to their unique properties. Titanium is a very strong and light metal. This property causes that titanium has the highest strength-to-weight ratio in comparison the other metal that are studied to medical use. Titanium is also incredibly durable and long-lasting. When titanium cages, rods, plates and pins are inserted into the body, they can last for upwards of 20 years. Titanium non-ferromagnetic property is another benefit, which allows patients with titanium implants to be safely examined with MRIs and NMRIs [4], [5]. Titanium and its alloys are used in many different industries such as biomedical applications, automobile, aerospace, chemical field, electronic, gas and food industry [6]. In recent decades, titanium is applied widely in biomedical and medical field because it is absolutely a proper joint with bone and other body tissue, immune from corrosion, strong, flexible and compatible with bone growth.

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Titanium is used in different medical applications such as dental implants, hip and knee replacement surgeries, external prostheses and surgical instruments [4], [7]. Elias C.N et al., studied the Bio Medical applications of Titanium and its alloy [8] and Kumar A et al., has done the investigations into machining characteristics commercially pure titanium using CNC electric discharge machining. On the other hand, there is some limitation for titanium use because of its initial high cost, availability, inherent properties and manufacturability [9]. Machining titanium and its alloys by conventional machining methods has some difficulties such as high cutting temperature and high tool wear ratio. Thus, titanium and its alloys are difficult-to-machine through conventional machining process. Therefore, unconventional machining processes are introduced for machining titanium and its alloys [2], [6]. Gu.L, Rajukar K.P et al., studied the electric discharge machining of Ti-6Al-4V with a bundled electrode.

Wire Electrical Discharge Machining (WEDM) technology has been widely used in tool and die-making industry, automotive, medical and practically any conductive materials. It is a non-traditional machining process which used the continuously circulating wire as electrode and cuts the work piece along a programmed path. Wire Electrical Discharge Machining (WEDM) known as wire-cut EDM, a thin single-strand metal wire is fed through the work piece submerged in a tank of dielectric fluid. WEDM is typically used to make punches, tools, and dies from hard metals that are difficult to machine with other methods. Wire-cutting EDM is commonly used when low residual stresses are desired, because it does not require high cutting forces for removal of material. If the energy per pulse is relatively low, little change in the mechanical properties of a material is expected due to these low residual stresses, although material that has not been stress-relieved can distort in the machining process. The work piece may undergo a significant thermal cycle, its severity depending on the technological parameters used. Such thermal cycles may cause formation of a recast layer on the part and residual tensile stresses on the work piece.

Titanium Ti-6Al-4V has become very popular materials and widely used as implants for dental, restorations and orthodontic wires, as well as orthopaedic due to their low density, high corrosion resistance and excellent mechanical properties [10]. However these alloys were very difficult to fabricate as they are not ductile and have low fracture toughness at room temperature [11]. Furthermore, due to its excellent strength property, it is found that it is extremely difficult to machine by conventional method. Several researchers [12], [13] have been investigated the different aspects of machining but no comprehensive research work has been reported so far in the field of wire electrical discharge machining of this alloy. Hence, it is essential to introduce an alternative method in machining of this alloy. Wire electrical discharge machining (WEDM) becomes an important non-traditional machining process due to its competency in machining of work pieces with complex geometry and hard stiffness [14]. The material is removed by a series of discrete electrical discharges between the wire electrode and the work piece in this process. The discharges, which are highly focused by the dielectric medium, cause rise in the local temperatures of the work piece near the point of introduction. The temperatures are high enough to melt and vaporize the material in the immediate vicinity of the electrical discharges. Since, there is no mechanical contact between the work piece and the electrode, material of any hardness can be machined as long as it is electrically conductive [15]. Due to this reason, it has dramatically increased in high application of materials with high stiffness in the aerospace, nuclear, and automotive industries. WEDM was effective solutions for machining hard materials such as titanium, molybdenum, zirconium and tungsten carbide with complex shapes and profiles that are difficult to machine using conventional methods [16], [17]. The improper selection of parameters leads to wire breakage and certain limits on the cutting speed, which in turn reduces productivity. The selection of optimum cutting parameters is the solution in obtaining a higher cutting speed or good surface finish. However, even though with the up to- date CNC WEDM machines exist, the problem of selecting optimum cutting parameters for WEDM processes is not fully solved. Machine feed rate, discharge current, wire speed, wire tension and average working voltage are the machining parameters which affect WEDM performance measures [18], [19]. This study aimed in achieving the appropriate conditions in machining Ti-6Al-4V Titanium alloy resulted in term of surface roughness and the surface topography of the WEDM surface.

2. EXPERIMENTAL WORK

The experiments were conducted on ULTRACUT S1 Four Axis Wire Cut EDM machine from Electronica India Pvt. Ltd. The titanium alloy of Ti 6Al 4V was used as work piece material for the present Investigations. The chemical composition of Ti-6Al-4V titanium alloy by % weight is given in Table 1. A diffused brass wire of 0.3 mm diameter was used as the wire electrode due to its extreme properties like electric discharge performance, heat resistance, low calorification and heat release. The chemical composition of brass wire was 63% copper and 37% Zinc by weight and its tensile strength is 142000 PSI. The deionized water was used as dielectric because of its low viscosity and rapid cooling rate and its temperature was kept at 20ºC. The process parameters such as pulse on time, pulse off time, pulse current, server voltage and wire tension has taken at three different levels as shown in Table 2 and experiments were conducted on WEDM machine with brass electrode of diameter 0.3 mm. The selections of these factors were based on the suggestions from the handbook recommended by the machine manufacturer, preliminary research results and journals. The surface roughness was measured with S1500DX/SD2 model SURFCOM with sensitivity of ½ Max and at magnification of X10000 and the surface topography has been observed with the Hitachi 3400N model Scanning Electron Microscope (SEM) at magnification of X2000. The influence of WEDM process parameters such as pulse on time, pulse off time, input power, servo reference voltage and wire tension on process performance of Surface Roughness and surface topography of the wire electric discharge machined surface have been investigated.

TABLE 1

CHEMICAL COMPOSITION OF TI-6AL-4V TITANIUM ALLOY

C	Fe	Al	O_2	N_2	V	H_2	Ti
0.08	0.22	6.08	0.02	0.05	4.02	0.15	Balance

TABLE 2

TEST CONDITIONS

Process Parameter	L1	L2	L3
Pulse on Time (T_{on} in µs)	100	110	120
Pulse off Time (T_{off} in µs)	40	50	60
Servo Voltage (SV in V)	40	50	60
Input Power (IP in m/c units)	10	11	12
Wire Tension (WT in kgf)	1.1	1.3	1.5

3. RESULTS AND DISCUSSIONS

3.1 Surface Roughness

Response surface methodology approach is the procedure for determining the relationship between various process parameters with various machining criteria and exploring the effects of these process parameters on the coupled responses [20]. In order to study the effect of WEDM process parameters of Ti-6Al-4V Titanium alloy on Surface Roughness, a second order polynomial response can be fitted [21]. In this investigation total 32 experiments were conducted. The Design Expert 7 soft ware was used for regression and graphical analysis of the data obtained. The optimum values of selected variables were obtained by solving the regression equations and by analyzing the response surface contour plots. Analysis of variance (ANOVA) was used to analyze the experimental data and the relative significance of the machining parameters with respect to the measure of performance was investigated. The analysis of variance based on partial sum of squares is shown in table 3.

TABLE 3

ANALYSIS OF VARIANCE TABLE [PARTIAL SUM OF SQUARES]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	17.27598	12	1.439665	47.93974	0.0001
A-T_{on}	15.03896	1	15.03896	500.7858	0.0001
B-T_{off}	0.225344	1	0.225344	7.503791	0.0130
C-SV	0.006923	1	0.006923	0.230521	0.0366
D-IP	0.229165	1	0.229165	7.631004	0.0124
E-WT	8.89E-05	1	8.89E-05	0.00296	0.0472
AB	0.226814	1	0.226814	7.552736	0.0128
BC	0.214138	1	0.214138	7.130618	0.0151
DE	0.161403	1	0.161403	5.374599	0.0317
B^2	0.728484	1	0.728484	24.25797	0.0001
C^2	0.478371	1	0.478371	15.92937	0.0008
D^2	0.118962	1	0.118962	3.961351	0.0611
E^2	0.17641	1	0.17641	5.874317	0.0255

The Model F-value of 47.94 implies that the model is significant. There is only a 0.01% chance that a 'Model F-Value' this large could occur due to noise. The values of 'Prob > F' is less than 0.0500 indicate that the model terms are significant. In this case A, B, C, D, E, AB, BC, DE, B^2, C^2, E^2 are significant model terms. The 'Pred R-Squared' of 0.8847 is in reasonable agreement with the 'Adj R-Squared' of 0.9478. 'Adeq Precision' measures the signal to noise ratio. A ratio greater than 4 is desirable and this ratio of 22.755 indicates an adequate signal. After eliminating the non-significant terms, the final response equations for Surface Roughness is found as follow:

$$R_a = -9.95433 + 0.031874 * T_{on} + 0.351832 * T_{off} - 0.48885 * SV + 4.167019 * IP - 22.4483 * WT + 0.001191 * T_{on} * T_{off} + 0.001157 * T_{off} * SV + 0.502188 * IP * WT - 0.00529 * T_{off}^2 + 0.00429 * SV^2 - 0.21396 * IP^2 + 6.513603 * WT^2$$

Normal probability plot of the studentized residuals checked to know the normality of residuals, studentized residuals versus predicted values checked to know the constant error as shown in figure 1 & 2 respectively and the externally studentized residuals checked to look for outliers and Box-Cox plot for power transformations.

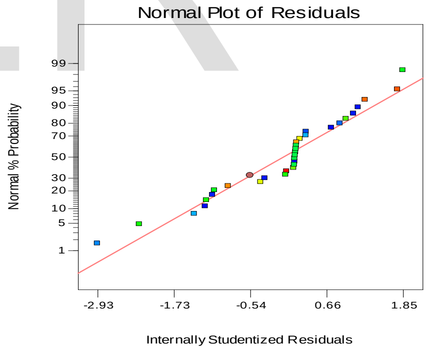

Fig. 1 Normal probability plot

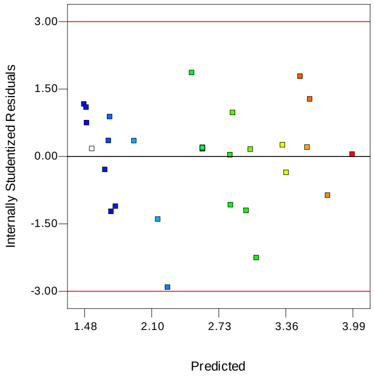

Fig. 2 Studentized Residuals vs. Predicted values

The effects of input process parameters such as pulse on time, pulse off time, pulse current, servo voltage and wire tension on response variable of surface roughness was analyzed on the basis of mathematical relationship obtained through experimental results and response surface methodology. Figure 3 shows the response surface plot for surface roughness versus pulse on time and pulse off time. From this figure it is observed that as the pulse on time increases the surface roughness also increases, but the surface roughness decreases as the pulse off time increases and improves quality of surface. Figure 4 shows the response surface plot for surface roughness versus pulse current and servo voltage. From this figure it is observed that the surface roughness increases as the pulse current and servo voltage increases. However, for extended pulse current and servo voltage the surface roughness decreases.

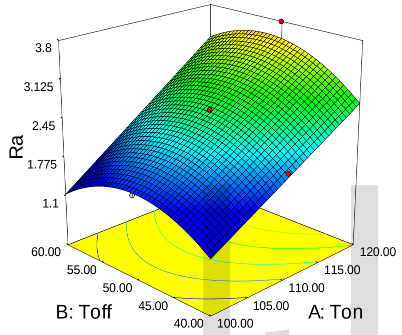

Fig. 3 Response surface plot (T_{on} and T_{off} versus Surface Roughness)

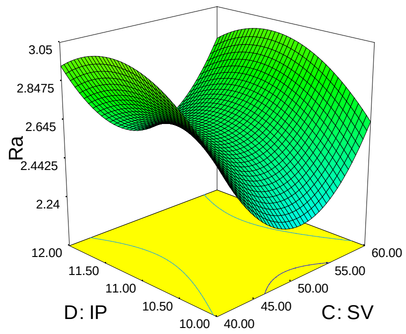

Fig. 4 Response surface plot (IP and SV versus Surface Roughness)

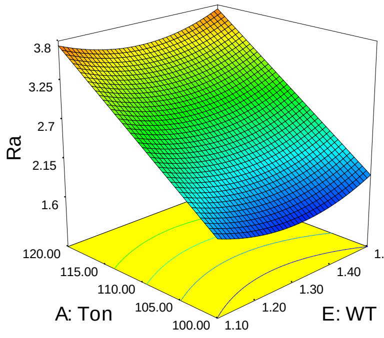

Fig. 5 Response surface plot (T_{on} and WT versus Surface Roughness)

Figure 5 shows the response surface plot for surface roughness versus pulse on time and wire tension. From this figure it is observed that the surface roughness increases as the pulse on time increases, as the wire tension increases it reduces the vibrations of wire and causes reduction in surface roughness and improves the quality of the machined surface. Further, the experimental values reveal that as the pulse on time/pulse duration and input power increases, the discharge energy increases and the longer discharge energy produces large craters on machined surface and increases surface roughness. As and when the wire tension and servo voltage increases the surface roughness decreases and it improves the quality of machined surface. From the ANOVA it is observed that the pulse on time and pulse current are the dominant factors. Pulse on time, pulse current, pulse off time, servo voltage and wire tension and their interactions pulse off time and input power, servo voltage and input power, pulse on time and pulse off time and pulse on time and servo voltage are the significant factor for surface roughness.

3.2 Surface topography

The surface topography/surface integrity of the machined surface of Ti-6Al-4V titanium alloy was examined by conducting SEM analysis. Figure 6 shows the SEM micrograph of machined surfaces at different pulse on time settings i.e. at 100 μs and 120 μs, Figure 7 show the SEM micrograph of machined surfaces at different pulse off time settings i.e. at 40 μs and 60 μs, Figure 8 shows the SEM micrograph of machined surfaces at different pulse current settings i.e. at 10 and 12 machine units, Figure 9 shows the SEM micrograph of machined surfaces at different servo voltage settings i.e. at 40 V and 60 V and Figure 10 shows the SEM micrograph of machined surfaces at different wire tension settings i.e. at 1.1 kgf and 1.5 kgf respectively. From these SEM micrographs it is observed that the peaks and valleys, micro holes and surface defects are very low and minor at lower range values of input parameters and the surface is abounds with moderate to large peaks and valleys, micro holes, surface cuts as and when the process input parameters are increased. Further, it is observed from these SEM micro graphs that the machined surface is full of craters and black patches at higher range of input parameters due to arcing during machining. From these results it is observed that the lower or moderate range of input process parameters can give better surface quality than the highest range values of input process parameters.

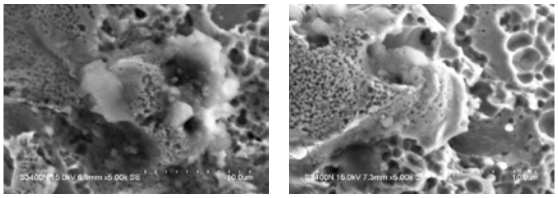
"(a)" "(b)"

Fig. 6 SEM micro graphs at (a) T_{on} = 100 µs & (b) T_{on} = 120 µs

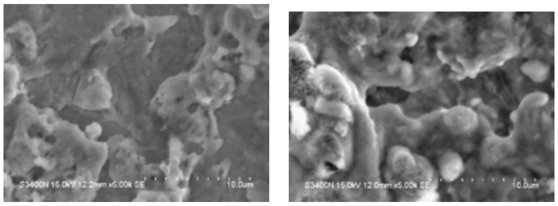
"(a)" "(b)"

Fig. 7 SEM micro graphs at (a) T_{off} = 40 µs & (b) T_{off} = 60 µs

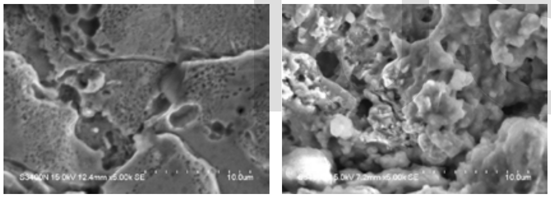
"(a)" "(b)"

Fig. 8 SEM micro graphs at (a) IP = 10 & (b) IP = 12

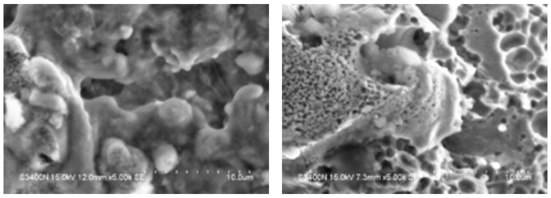
"(a)" "(b)"

Fig. 9 SEM micro graphs at (a) SV= 40V & (b) SV=60V

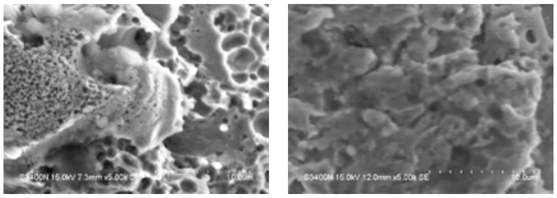
"(a)" "(b)"

Fig. 10 SEM micro graphs at (a) WT = 1.1 kgf & (b) WT = 1.5 kgf

4. CONCLUSIONS

In this study, the influence of wire electric discharge machining parameters such as pulse on time, pulse off time, input power, server voltage and wire tension on surface roughness and surface topography of wire electric discharge machined surface of Titanium alloy workpiece have been investigated. Based on the experimental results the following conclusions are made:

- As the pulse on time/pulse duration and input power increases, the surface roughness also increases because of high discharge energy produces large craters on machined surface. As and when the wire tension and servo voltage increases the surface roughness decreases and it improves the quality of machined surface.
- From ANOVA it is observed that pulse on time, pulse current, pulse off time, servo voltage and wire tension and their interactions pulse off time and input power, servo voltage and input power, pulse on time and pulse off time and pulse on time and servo voltage are the significant factor for surface roughness.
- It is observed from the SEM micro graphs that at low level values of the input process parameters the peaks and valleys, micro holes and surface defects are very low and minor and the peaks and valleys, micro holes and surface defects are very high as and when the input process parameters are increased and the machined surface is full of craters and black patches at higher range of input parameters due to arcing during machining. Further, it is observed that the lower or moderate range of input process parameters can give better surface quality than the highest range values of input process parameters.

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