Investigation into application of electrical discharge machining as a surface treatment process

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Abstract: - Titanium alloys are recognized as difficult o machine materials because of their susceptibility to work hardening during machining by conventional machining processes. This problem can be overcome by using electrical discharge machining (EDM) an unconventional machining process. In some of the researches it is reported that machining of workpiece by using EDM process modifies the surface properties of the base material. Hence, the objective of this study is to investigate the improvement in surface properties of titanium alloy (Grade 5) machined by die sinking EDM process using graphite electrode. Gap current, pulse on time, and pulse off time were taken as EDM process parameter and micro-hardness was taken as the response characteristics. From the experimental analysis it was found that pulse off time plays an important role in enhancing the surface hardness of the specimen. This is due to migration of carbon from the tool electrode and dielectric onto the surface of workpiece. This increase in the micro hardness can be taken as the indicator of surface alloy. Presence of titanium carbide (TiC) indicates that its formation is taking place in the plasma channel and the same was confirmed by the X-ray diffraction analysis.

Key-Words: -Ti alloy, Electrical discharge machining, Scanning electron microscopy, X-ray diffraction, Micro hardness .

1 Introduction

Many decades ago titanium was considered as rare metal, but nowadays it is one of the most important metals in the industry. Pure titanium can be alloyed with various elements to produce light weight alloys. Due to its high strength-to-weight ratio and corrosion resistance properties at room and elevated temperatures make it attractive for many applications including aircraft, jet engines, racing cars, biomaterials such as orthopaedic implants,

marine components etc. Generally the machining of Ti and its alloys is very difficult owing to several inherent properties of the material. Ti is very chemically reactive and therefore, has a tendency to weld to the cutting tool during machining thus, leading to premature tool failure [1]-[2]. Soni and Chakraverti, 1994 investigated EDM of Ti alloy with a copper-tungsten electrode in respect of MRR, electrode wear, and surface roughness by varying currents and electrode rotation was carried out [3]. Soni investigated the formation of debris during rotary electro discharge machining of titanium alloy (Ti-6Al-4V) and die steel high carbon high chromium (T 215 Cr 12) was carried out and it was observed that the chemical composition of these particles differs considerably, from its parent material due to migration of material from the rotating copper-tungsten electrode and dielectric fluid [4]. Chow et al. modified conventional EDM with an advanced control circuit, was used to minimise the output current. Micro-slit EDM by applying a thin rotational copper diskette electrode with various dielectric fluids namely: kerosene, kerosene with aluminium powder and kerosene with silicon carbide powder was used to machine titanium alloy (Ti-6Al-4V). The features of this revised EDM were studied by assessing the surface roughness, the material removal depth, the electrode wear rate and the slit expansion [5]. Lin et al. investigated the machining characteristics of titanium alloy (Ti-6Al-4V) using a combination process of EDM with USM to improve the machining efficiency and accuracy. From the experimental results, it was concluded that the combined process EDM/USM can increase the MRR and decrease the thickness of the recast layer [6]. Wansheng et al. introduced ultrasonic vibration into the micro-EDM and experiments results have shown that holes with a diameter of less than 0.2 mm and a depth/ diameter ratio of more than 15 can be drilled steadily [7]. Researchers have investigated the modifying machined surfaces by applying PM method to fabricate electrodes in an EDM process, and found that the electrode elements could migrate to the machined surface to form an alloying layer that effectively increases the wear resistance of the machined surface [8]-[10]. Yan et al. pointed out that the machining characteristic on pure titanium was influenced with the addition of urea into distilled water. Adding urea into the dielectric, MRR and EWR increased with increase in peak current but the surface roughness deteriorated [11]. Ho et al. used solid and PM compacted copper electrodes with a commercial water-based dielectric fluid for the machining of alloying α-β titanium (Ti-6Al-4V) for surface modification. When using the solid copper electrode under negative polarity however, a substantial increase in micro hardness was measured, probably due to the formation of TiO_2 [12]. Fonda et al. investigated the effect of Ti-6Al-4V's thermal and electrical properties on the EDM productivity. Temperature measurements have been made for Ti-6Al-4Vworkpieces with various duty factors to observe the optimal duty factor in terms of productivity and quality. The resulting temperature measurements show that as the duty factor increases, the internal work piece temperature also increases. Beyond a certain duty factor, the temperature begins to steadily increase, which causes poor machining productivity and quality. At lower duty factors of 3% and 7%, the surface profiles are more uniform than those at higher duty factors [13]. Furutani et al. investigated the influence of discharge current and pulsed duration on the titanium carbide deposition in EDM of titanium powder suspended in dielectric [14]. Kao et al. optimised the parameters of EDM process to Ti-6Al-4V alloy considering multiple performance characteristics using the Taguchi method and grey relational analysis and which results in an improved electrode wear ratio of 15%, MRR of 12% and surface roughness of 19% [15]. Kumar et al. (2012) presented a review paper on the fundamental principles of EDM and work done with regard to effect of operating parameters on material removal rate (MRR), tool wear rate (TWR), surface roughness and surface improvements on titanium alloys work piece [16]. Based on the literature review it can be concluded that very little work has been reported with regard to surface modification of titanium alloys using electrical discharge machining process. Thus the objective of this study is to investigate the improvement in the surface properties of Ti alloy machined by graphite electrode in die sink electrical discharge machine.

2 Materials and Methods

Experiments were carried on die-sink type electrical discharge machine of model C 400 x 250 of Electronica Machine Tools Limited make with NC control in Z-axis and negative polarity for electrode. Commercial grade EDM oil was used as dielectric fluid and side flushing pressure of 0.5 kg/cm^2 was employed for carrying out experiments. Titanium alloy of garde 5 is considered as workpiece material and graphite was considered as tool electrode material. Work piece of size 15 mm x 13 mm x 10 mm and tool electrode of dia 12 mm by 50 mm length were employed for experimentation.

Experiments were carried out as per the L_9 (3^4) orthogonal array as shown in table 1. After machining, the surfaces were washed with oil to remove any accumulated debris at the corners followed by acetone cleaning. All the machined surfaces thus obtained were subjected to micro-hardness testing using a load of 1000 g for duration of 20 seconds. Before and after machining the micro-hardness was measured at five different places and average values were noted. Scanning electron microscopy was used to analyze the structural features of the machined surfaces. In this study, the EDMed samples were analysed by scanning electron microscopy at IISER, Pune which had a vacuum level of 10^{-5} torr. The XRD analysis was performed to determine the crystalline structure of the EDMed titanium alloy and to analyse the formation of carbides. The machine used was high resolution Bruker D8 advanced system from Department of Physics, University of Pune.

Table 1 Experimental layout with observed values

Trial conditions	Gap current I_g (A)	Pulse on time, T_{on} (µs)	Pulse off time T_{off} (µs)	Micro hardness (HV)
1	2	8	7	389.000
2	2	23	8	591.070
3	2	38	9	441.067
4	4	8	9	575.433
5	4	23	7	662.033
6	4	38	8	500.060
7	6	8	8	777.070
8	6	23	9	952.670
9	6	38	7	865.640

3 Results and Discussions

Experiments were conducted by using the parametric approach of the Taguchi's method and table 1 shows the orthogonal array with observed values. Regression analysis has been performed to find out the relationship between input factors and responses using Minitab 16 statistical software. During regression analysis it was assumed that the factors and the responses are linearly related to each other. The average values of micro hardness for each parameter at levels 1, 2 and 3 for raw data and S/N data are plotted in figures 1 and 2. It is seen from the figures 1 and 2 that micro hardness increases with increase in gap current and for pulse on time micro hardness show an optimum at 23 µs. Similarly for pulse off time micro hardness shows an optimum at 8 µs.

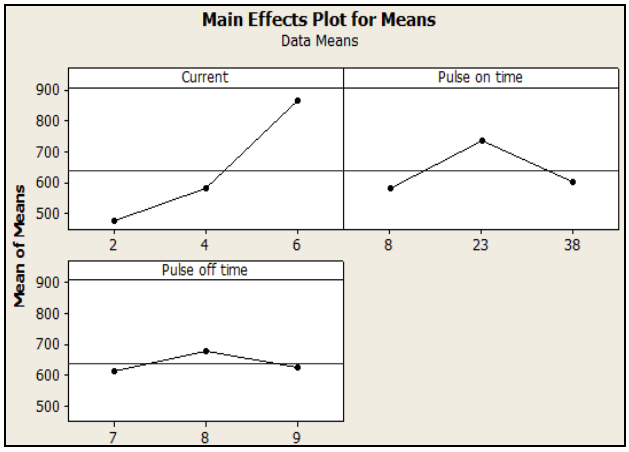

Fig.1 Effects of process parameters on micro hardness (raw data)

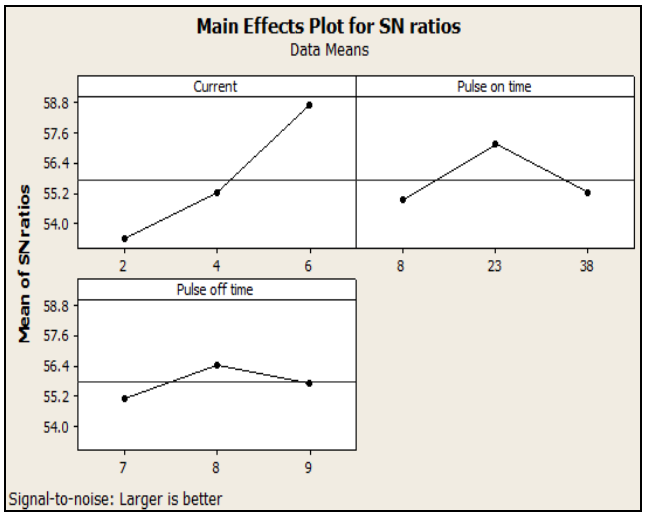

Fig.2 Effects of process parameters on micro hardness (S/N data)

The mean micro hardness of parent materials before machining was measured as 337 HV. After machining the resultant increase in micro hardness was observed for all trials conditions (table 1). The increase in current from 2 A to 6 A showed an increase in micro hardness of the machined surface. Increase in pulse on time from 8 µs to 38 µs resulted in improved micro hardness of the machined surface due to higher amount of energy supply. Increase in pulse off time from 7 µs to 9 µs resulted in increase in micro hardness of the machined surface. This increase can be attributed to the effect of melting and resolidified layer on the machined surface. The increase in micro hardness can also be attributed to

migration of carbon resulting in formation of cementite and transfer of alloying elements to the machined surface. This type of migration results in formation of independent hard carbides. Out of the nine trial conditions trial numbers 7 and 8 shows more than 100 % increase in the micro hardness of the EDMed surface. For trail condition 8, material accretion study was carried out using scanning electron microscopy. To confirm the formation of hard carbides on to the EDMed surface XRD analysis was done.

Table 2 Analysis of variance for micro hardness (S/N data)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Current	2	44.1586	44.1586	22.0793	520.09	0.002
Pulse on time	2	8.6970	8.6970	4.3485	102.43	0.010
Pulse off time	2	2.7090	2.7090	1.3545	31.91	0.030
Residual Error	2	0.0849	0.0849	0.0425		
Total	8	55.6495				
DF- degrees of freedom, SS- sum of squares, MS-mean squares, F- ratio of variance of a source to variance of error, P < 0.05- determines significance of a factor at 95% confidence level						
S = 0.2060 R-Sq = 99.8% R-Sq(adj) = 99.4%						

Table 3 Analysis of variance for micro hardness (raw data)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Current	2	246096	246096	123048	144.76	0.007
Pulse on time	2	42112	42112	21056	24.77	0.039
Pulse off time	2	6759	6759	3379	3.98	0.201
Residual Error	2	1700	1700	850		
Total	8	296667				
DF- degrees of freedom, SS- sum of squares, MS-mean squares, F- ratio of variance of a source to variance of error, P < 0.05- determines significance of a factor at 95% confidence level						
S = 29.16 R-Sq = 99.4% R-Sq(adj) = 97.7%						

Table 4 Response table for micro hardness (S/N data)

Level	Current	Pulse on time	Pulse off time
1	53.37	54.94	55.12
2	55.20	57.14	56.46
3	58.71	55.21	55.71
Delta	5.34	2.21	1.34
Rank	1	2	3

Table 5 Response table for micro hardness (raw data)

Level	Current	Pulse on time	Pulse off time
1	473.7	580.5	613.9
2	579.2	735.3	677.4
3	865.1	602.3	626.7
Delta	391.4	154.8	63.5
Rank	1	2	3

In order to study the significance of the process variables towards micro hardness, analysis of variance (ANOVA) was performed. It was found that gap current, pulse on time and pulse off time are significant process parameter for micro hardness. Table 2 and 3 shows the ANOVA table of the S/N data and the raw data for micro hardness respectively. The response table 4 and 5 show the average of each response characteristics (S/N data and raw data) for each level of each factor. The tables include ranks based on delta statistics, which compare the relative magnitude of effects. The delta statistic is highest minus the lowest average for each factor. Minitab assigns ranks based on delta values; rank 1 to the highest delta value, rank 2 to the second highest, and so on. The ranks indicate the relative importance of each factor to the response. The ranks and the delta values for various parameters show that gap current has the greatest effect on micro hardness and is followed by pulse on time and pulse off time. As micro hardness is the "highest the better" type quality characteristic, from figure 1, it can be seen that the third level of gap current (A3), second level of pulse on time (B2) and second level of pulse off time (C2) result in maximum value of micro hardness. The S/N ratio analysis (figure 2) also suggests the same levels of the variables (A3B2C2) as the best levels for maximum micro hardness in EDM process.

Regression analysis was carried out to ensure a least squared fitting to error surface in Minitab 16 environment. Regression analysis has been performed to find out the relationship between input factors and micro hardness. During regression analysis it was assumed that the factors and the response are linearly related to each other. The general first order model was developed to predict the micro hardness over the experimental region (equation 1). In general, the R^2adjustedstatistic will not always increase as variables are added to the model. In fact, if unnecessary terms are added, the value of R^2adjusted will often decrease. When R^2 and R^2 adjusted differ dramatically, there is a good chance that no significant terms have been included

in the model. For this experiment the R^2 value indicates that the predictors explain 83.70% of the response variation. Adjusted R^2 for the number of predictors in the model 81.58% values shows that the data are fitted well.

HV = 179.992 + 97.8536 x (current) + 0.725156 x (pulse on time) + 6.40667 x (pulse off time) (1)

The positive value of gap current, pulse on time and pulse off time is indicative that increase in process parameters increases the micro hardness. Table 6 shows the micro hardness values predicted from the obtained model, experimental values and percentage error. From this validation test it was found that empirical model obtained from multiple regression method can predict response values with an average of 11.6% error. This shows a good agreement between predicted and experimental values.

Table 6 Empirical model validation test results

Trial No.	Predicted values	Experimental values	Percentage error
1	426.3471	389.000	9.6
2	443.6311	591.070	25
3	460.9152	441.067	4.5
4	634.8677	575.433	10.3
5	632.9317	662.033	4.4
6	650.2157	500.060	30
7	824.1682	777.070	6
8	841.4522	952.670	11.6
9	839.5162	865.640	3

The optimal levels of the process parameters for micro hardness were predicted considering the effect of the significant parameters. The average values of the micro hardness obtained through the confirmation experiments must lie within the 95% confidence interval, CI_{CE}. However, the average values of micro hardness obtained from the confirmation experiments may or may not lie within 95% confidence interval, CI_{POP}. The optimum value of micro hardness at the optimal levels of significant variables which have been selected as gap current (A3), pulse on time (B2) and pulse off time (C2) from figure 1 and table 3. The estimated mean of the micro hardness can be determined [17] from equation 2.

$$\mu_{HV} = A_3 + B_2 + C_2 - 2T \quad (2)$$

Where,

T = overall mean of micro hardness = R/9 = 639.3 HV (R values were taken from table1)
From table 5 values of A_3, B_2, C_2 are selected as
A_3 = average value of micro hardness at third level of gap current = 865.1 HV
B_2 = average value of micro hardness at second level of pulse on time = 735.3 HV
C_2= average value of micro hardness at second level of pulse off time = 677.4 HV

Substituting the values of various terms in the above equation,
$\mu_{HV} = 865.1 + 735.3 + 677.4 - 2\,(639.3) = 999.4$ HV

The 95% confidence intervals of confirmation experiments (CI_{CE}) and population (CI_{POP}) are calculated by using equations 3 and 4 respectively.

$$CI_{CE} = \sqrt{F_\alpha\,(1, f_e)\,V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad (3)$$

$$CI_{POP} = \sqrt{\frac{F_\alpha\,(1, f_e)\,V_e}{n_{eff}}} \quad (4)$$

Where, $F_\alpha\,(1, f_e)$ = The F-ratio at the confidence level of $(1-\alpha)$ against DOF 1 and error degree of freedom f_e.

$$n_{eff} = \frac{N}{1 + [\text{DOF associated in the estimate of mean response}]}$$

= 9/ (1+6) = 1.285
N = Total number of results = 9
R = sample size for confirmation experiments = 3
V_e = error variance = 850 (table 3)
f_e = error DOF = 2 (table 3)
$F_{0.05}\,(1,2)$ = 18.51 (tabulated F value [17])
CI_{CE} = ± 132.24
CI_{POP} = ± 110.65

Therefore, the predicted confidence interval for confirmation experiments is:

$$\text{Mean } \mu_{HV} - CI_{CE} < \mu_{HV} < \text{Mean } \mu_{HV} + CI_{CE}$$

$$867.16 < \mu_{HV} < 1131.64$$

The 95% confidence interval of the population is:

$$\text{Mean } \mu_{HV} - CI_{POP} < \mu_{HV} < \text{Mean } \mu_{HV} + CI_{POP}$$

$$888.75 < \mu_{HV} < 1110.05$$

In order to validate the results obtained, three confirmation experiments were conducted for micro hardness at optimal levels of the process variables. The average values of the characteristics were obtained and compared with the predicted values. The result is given in table 7. The value of micro hardness obtained through confirmation experiments are within the 95% of CI_{CE} of micro hardness. It is observed that the optimal values are within the specified range of process variables.

Optimal set of parameters	Predicted optimal value	Predicted confidence intervals at 95% confidence level	Actual value (average of three confirmation experiments)
A3B2C2	999.4HV	CI_{CE}: 867.16 < μ_{HV} < 1131.64 CI_{POP}: 888.75 < μ_{HV} < 1110.05	972.67 HV

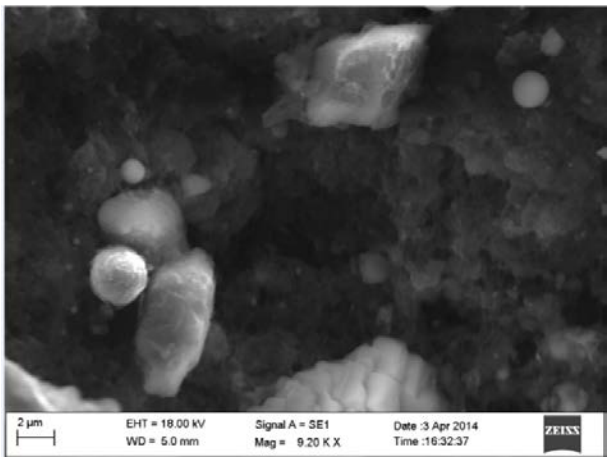

Fig.3 Accretion at 6 A gap current, 23 µs pulse on time and 8 µs pulse off time

Figure 3 shows the SEM image for accretion on machined surface at 6 A gap current, 23 µs pulse on time and 8 µs pulse off time. And figure 4 shows the SEM image for accretion of machined surface at 6 A gap current, 23 µs pulse on time and 9 µs pulse off time. From the SEM image it is seen that the accretion is porous and deposition is not uniform over the surface of specimen. A thick accretion is observed at negative polarity of the electrode.

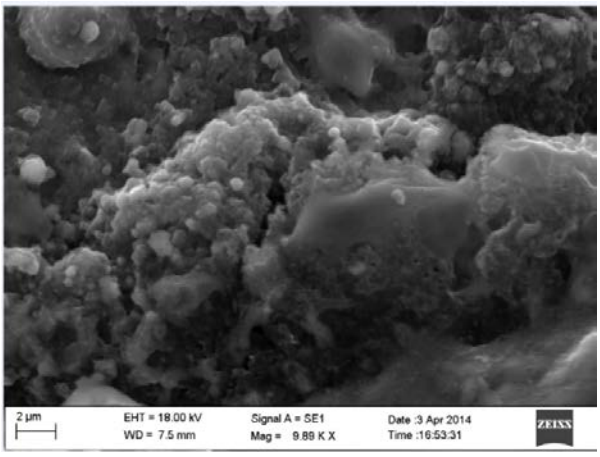

Fig.4 Accretion at 6 A gap current, 23 µs pulse on time and 9 µs pulse off time

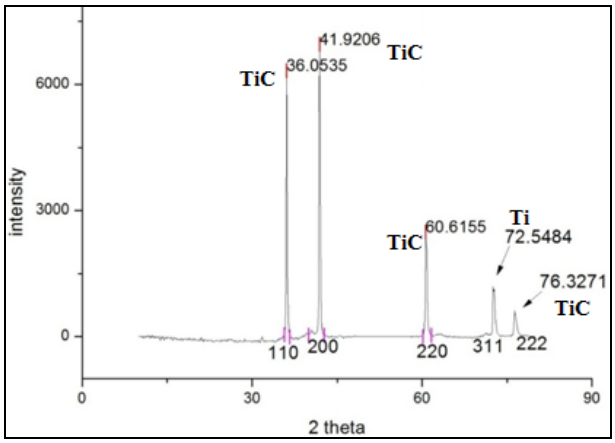

Fig.5 XRD of EDMed surface at 6 A gap current, 23 µs pulse on time and 8 µs pulse off time

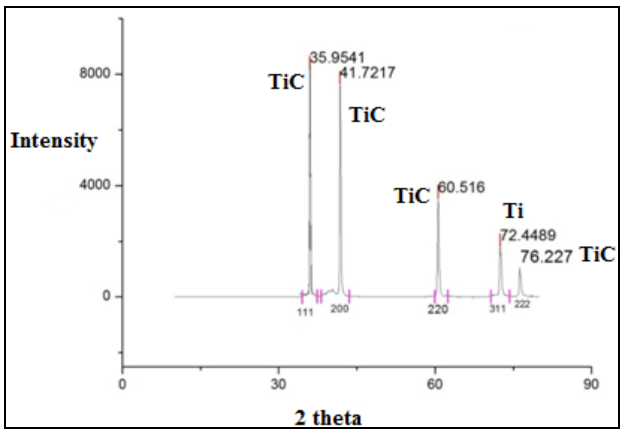

Fig.6 XRD of EDMed surface at 6 A gap current, 23 µs pulse on time and 9 µs pulse off time

Figure 5 and 6 shows an analysis result by XRD at 6 A gap current, 23 µs pulse on time and 8 µs pulse off time and at 6 A gap current, 23 µs pulse on time and 9 µs pulse off time respectively. Some

angles with respect to Ti and TiC are observed on the surface of specimen. This confirms the migration of carbon from the dielectric onto the titanium alloy surface.

4 Conclusions

This study was carried out to investigate the surface modification and deposition on titanium alloy using die sinking EDM process by graphite electrode. Gap current, pulse on time, and pulse off time were taken as EDM process parameter and increase in micro hardness of EDMed surface was taken as an indicator of surface improvement. The maximum increase in micro hardness of more than 100 % was observed in most the experiments. This increase is due to migration of carbon from the tool electrode and dielectric onto the surface of workpiece. Presence of TiC indicates that its surface alloying is taking place on the surface of Ti alloy and the same was confirmed by the X-ray diffraction analysis.

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