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Experimental Investigation of Wire-EDM Process Parameters on MRR of Ti-6al-4v Alloy

Parveen Kr. Saini, Mukesh Verma

Abstract - The objective of the present work was to investigate the effect of the wire electrical discharge machining process parameters on material removal rate of titanium alloy using Taguchi approach. A brass wire of 250µm was applied as a tool electrode to cut the specimen. L_{36} mixed orthogonal array ($2^1 \times 3^8$) has been selected for experimentation under different variables like dielectric conductivity, pulse width, time between pulses, maximum feed rate, servo control mean reference voltage, short pulse time, wire feed rate, wire mechanical tension and injection pressure. The predicted optimal setting of process parameters for material removal rate has been obtained and analyzed by using Taguchi method. The significant process parameters have also been identified and their effects on material removal rate have been studied in detail. The predicted value for MRR at optimal parameter setting is 28.483mm^3/min and the experimental average value for MRR at optimal parameter setting is 27.584mm^3/min. So the above mathematical prediction for MRR using MINITAB 15 is validated by confirmation experiment with percentage error of 3.25%.

Keywords - Titanium alloy, Material removal rate, Taguchi approach, Wire-EDM

I. INTRODUCTION

Accompanying the development of mechanical industry, the demands for alloy materials having high hardness, toughness and impact resistance are increasing. Wire EDM machines are used to cut conductive metals of any hardness or that are difficult or impossible to cut with traditional methods. The consistent quality of parts being machined in wire electrical discharge machining is difficult because the process parameters cannot be controlled effectively. These are the biggest challenges for the researchers and practicing engineers. Keeping in view the applications of material titanium alloys, it has been selected and has been machined on wire-cut EDM. Wire cut electrical discharge machining (WEDM) or Electrical discharge wire cutting is a spark erosion process used to produce two and three dimensional complex shapes through electrically conductive workpieces. In WEDM process, a small diameter wire ranging from 0.05 to 0.25 mm is applied as the tool electrode

A DC power supply delivers high-frequency pulses of electricity to the wire and the workpiece. The gap between the wire and workpiece is flooded with deionized water, which acts as the dielectric. Figure 1 shows the systematic diagram of the WEDM process.

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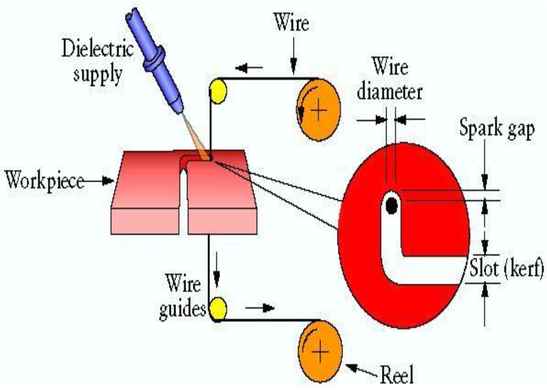

Fig. 1: Wire-EDM Process

Lok and Lee analyzed the machining of advanced ceramics (Sialon and Al_2-O_3-TiC) using the wire-cut EDM process. The author found that the volumetric material removal rate for machining ceramic materials were found to be very low as compared with alloy steels and the surface roughness achieved was generally inferior to that with the die sinking EDM process [1]. A data mining approach based on machine learning to model WEDM (Robofil 310) process used for machining titanium alloy using brass wire electrode. Authors suggested that hybrid approaches such as combination of artificial neural networks and decision trees might lead to improved performance and prediction accuracy [2]. Parametric Optimization of Wire Electrical Discharge Machining (WEDM) Process using Taguchi Method was analyzed for measuring are Surface finish (Ra) and MRR [3]. The Author studied the optimum cutting conditions for the WEDM of γ titanium aluminide alloy using brass wire electrode with an appropriate wire offset setting in order to get the desired surface finish and dimensional accuracy. The author suggested that final set of 20 Pareto optimal solutions were very useful and will act as a guideline for optimum machining of γ titanium aluminide alloy [4]. Modeled and optimized the process parameters for the WEDM of γ-titanium aluminide using brass wire electrode during trim cutting operation. The experimental plan was based on the face centered, central composite design (CCD). The residual analysis and experimental result indicated that the proposed models could adequately describe the performance indicators within the limits of the factors [5]. An experimentally investigated the machining of B40 cemented carbides and Ti6Al4V titanium alloy by WEDM using uncoated brass wire, zinc oxide coated brass wire and brass (CuZn20) coated brass (CuZn50) wire electrode. Author found that the highest volumetric metal cutting efficiency for the WEDM of cemented carbides B40 was 9.1mm^3/min and it was 50% more than for the uncoated brass electrode and 17% more than for the zinc coated electrode.

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The highest volumetric metal cutting efficiency for the WEDM of the titanium alloys Ti-6Al-4V was 17.75mm^3/min and it was 18% more than for the uncoated brass electrode and 16% more than for the zinc coated electrode [6]. The author discussed about the wire EDM research involving the optimization of the process parameters surveying the influence of the various factors affecting the machining performance and productivity. The paper also highlights the adaptive monitoring and control of the process investigating the feasibility of the different control strategies of obtaining the optimal machining conditions [7]. Shah investigated the effect of all critical WEDM parameters of tungsten carbide material on machining characteristics such as material removal rate, surface roughness and kerf for the machining of tungsten carbide cobalt composites. Author concluded that the material thickness had little effect on the material removal rate and kerf but was significant factor in terms of surface roughness [8]. Kumar and Chalosgaonkar studied the effect of various process parameter of WEDM using Zn coated brass wire of 0.25 mm; and pure Ti (ASTM Grade 2) of 24.25 mm thickness as a work material. The effect of different process on different performance variables like cutting speed, machining time, surface roughness and weight of wire (consumed during machining of each sample) are investigated using one variable at a time approach [9]. The author described the influence of three different machine rates which are 2 mm/min, 4 mm/min and 6 mm/min with constant current (6A) with WEDM of Titanium Ti-6Al-4V [10]. The author observed that the best combination of machining parameter viz. machine feed rate (4 mm/min), wire speed (8 m/min), wire tension (1.4kg) and voltage (60V) were identified and highlights the importance of process parameters and different machining conditions on kerf width, MRR, surface roughness and surface topography.

Literature review reveals that most of the research work has been carried out for conventional materials only and very limited work was reported on the wire electrical discharge machining of titanium alloys (Ti-6Al-4V). In the present work titanium alloy is considered as a work material and brass wire considered as electrode. The predicted optimal settings of the parameters are determined, conducted and analyzed using Taguchi method. L_{36} mixed orthogonal array ($2^1 \times 3^8$) was selected to design the experiments and S/N ratio was conducted to find the optimal set of parameters for machining. Machining characteristics of Ti-6Al-4V have been explored using WEDM for their application in concerned manufacturing industry.

II. EXPERIMENTAL SETUP

The experiments were carried out on a wire-cut EDM machine (ELEKTRA SPRINTCUT 734) of Electronica Machine Tools Ltd. as shown in figure 2. In the present work titanium alloy (Ti-6Al-4V, composition: C=0. 1%, Fe=0. 30%, Al=6. 05%, O=0. 25%, N=0. 03%, V=4. 1%, H=0. 015% and balance Ti) with yield strength of 828 GPA, a density of 4.42 g/cm^{3}and hardness of 396 HV has been used as a workpiece material and brass wire of 250µm is used as electrode material. Dimensions of the work material used for all the experiments have been kept at 80mm x 50mm x 10mm.

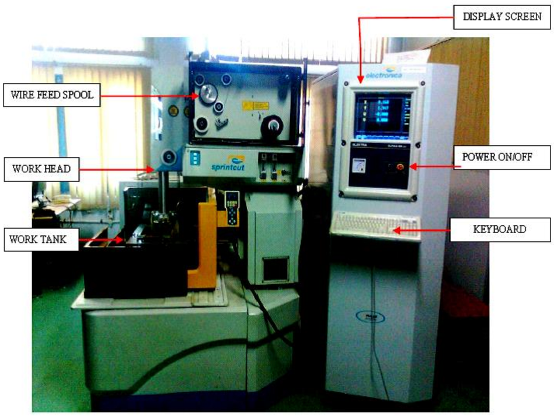

Fig. 2: Wire-cut EDM (ELEKTRA SPRINTCUT-734) of Electronica Machine Tools Ltd.

Performance of WEDM is evaluated on the basis of material removal rate (MRR). The mean cutting speed is calculated by the following relation:

Mean cutting speed= length of travel/ machining time.

Machining time is obtained from the computer, which is attached to the machine tool. The MRR is calculated utilizing the relation:

MRR = Mean cutting speed (V_c) × Thickness of the material (t) in mm × Width of cut (b) in mm

III. SELECTION OF PROCESS PARAMETERS

This paper makes use of Taguchi's method for designing the experiments. Hence L_{36} mixed orthogonal array ($2^1 \times 3^8$) was selected for the present investigation. The process parameters and their levels selected for final experimentation has been depicted in Table 1.

Table 1: Variable Process parameters and their values at different levels

Parameters	Units	Level 1	Level 2	Level 3
Dielectric conductivity (DC)	mho	10	14	
Pulse width (PW)	µs	0.6	0.8	1.2
Time between pulses (TBP)	µs	5	13	21
Maximum feed rate (MFR)	micron/ min.	2	12	22
Servo Control mean Reference Voltage (SCMRV)	volts	20	40	60
Short Pulse Time (SPT)	µs	0.2	0.4	0.6
Wire Feed Rate (WFR)	m/min	4	8	12
Wire Mechanical Tension (WMT)	daN	0.5	1.5	2.5
Injection Pressure (IP)	bars	2	3	4

IV. RESULTS AND DISCUSSIONS

In this research work, the effects of each machining

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parameters on material removal rate during machining of Ti-6Al-4V are analyzed. Table 2 represents the experimental results and S/N ratio for MRR. The response values from the experimental obtained mean data are used for analyzing the parametric effects on the material removal rate. The peak value of S/N ratio helps to identify the significant parameters and analyze their effects on the material removal rate.

Table 2: Experimental results and S/N ratio for MRR

Sr. No.	MRR (mm^3/min)			Mean	S/N ratio (dB)
	MRR_1	MRR_2	MRR_3		
1	21.250	21.622	19.141	20.6706	26.2689
2	18.385	18.865	14.971	17.4070	24.6724
3	23.153	19.005	11.697	17.9520	24.0003
4	19.881	19.636	20.323	19.9464	25.9947
5	17.009	21.638	17.071	18.5726	25.2173
6	25.824	14.810	13.597	18.0772	24.1765
7	13.310	13.782	11.280	12.7907	22.0369
8	21.978	20.202	16.365	19.5146	25.6041
9	23.439	26.329	23.896	24.5546	27.7693
10	19.475	14.579	14.300	16.1179	23.8963
11	15.894	12.831	12.994	13.9064	22.7422
12	25.919	23.028	23.531	24.1590	27.6275
13	22.371	17.891	22.269	20.8437	26.2350
14	13.276	11.928	10.087	11.7635	21.2434
15	21.586	17.045	20.360	19.6639	25.7402
16	16.295	14.163	14.917	15.1249	23.5505
17	24.023	11.318	13.005	16.1151	22.8811
18	22.427	25.554	26.465	24.8153	27.8275
19	19.330	19.736	10.478	16.5145	23.2018
20	15.980	17.278	20.462	17.9065	24.9240
21	16.865	19.609	20.397	18.9572	25.4668
22	19.912	18.354	18.037	18.7675	25.4442
23	18.070	14.765	18.379	17.0711	24.5139
24	19.732	24.752	20.619	21.7009	26.6069
25	15.517	13.732	15.586	14.9451	23.4445
26	23.133	22.445	28.296	24.6245	27.6932
27	22.399	15.661	11.422	16.4935	23.3925
28	15.557	17.317	10.289	14.3876	22.4890
29	24.207	20.345	15.565	20.0388	25.6066
30	15.933	17.269	11.149	14.7837	22.9136
31	10.643	11.056	8.710	10.1364	19.9725
32	24.401	24.684	18.072	22.3852	26.7210
33	22.670	21.934	22.484	22.3627	26.9879
34	16.175	17.499	12.269	15.3145	23.3942
35	16.953	11.915	12.529	13.7988	22.4939
36	20.369	22.023	20.382	20.9247	26.3958

Figure 3 show the effect of given parameters on material removal rate. MINITAB-15 software has been used to do the analysis of experiments so that the best optimal set of parameters can be obtained. The figure reveals that MRR increases with increase in PW, and SPT whereas MRR decrease with increase in TBP, SCMRV, WFR and WMT. This is due to the fact that discharge energy increases with increase in PW and SPT which lead to increase in MRR.

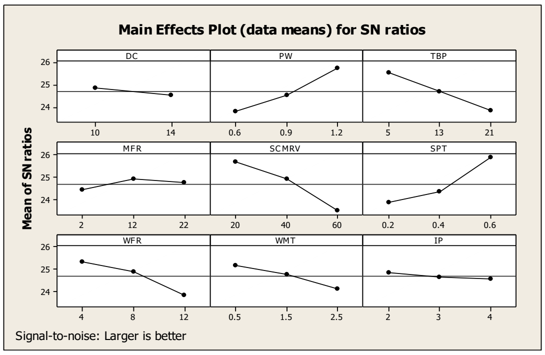

Fig. 3: Effect of process parameters on MRR

As TBP increases, the number of discharges within a given period becomes less which leads to decrease in MRR. Further with decrease in SCMRV, cutting velocity increases which results higher MRR. Energy carried away by wire increases if WFR increases so results the decrease in MRR. With the increase of WMT, spark gap decreases which further results the decrease in MRR. The process parameters DC, MFR and IP have no such significant effect on MRR because the change in the values of MRR with the change of DC, MFR and IP is very small.

A. Selection of Optimal Parameters and levels

Experimental analysis using pooled ANOVA predicts the significant process parameters and to establish the optimal parameter set of combinations for Wire-EDM of Ti-6Al-4V. Pooled analysis of variance (ANOVA) for MRR as shown in Table 3 reveals that short pulse time is recognized a higher significant process parameter with an F-value of 20.68 and P-value of 0.000 followed by pulse width, servo control mean reference voltage, time between pulses, wire mechanical tension and wire feed rate. In the present investigation, higher the better value for MRR is considered for analysis, so from this the optimal parameter set of combination for maximum MRR is $B_3C_1E_1F_3G_1H_1$. The table 4 shows the optimal parameter combinations with their levels for MRR.

Table 3: Pooled ANOVA Results for MRR

Source	DF	Seq SS	Adj MS	F	P
DC	Pooled				
PW	2	306.65	153.32	17.10	0.000
TBP	2	139.50	69.75	7.78	0.001
MFR	Pooled				
SCMRV	2	242.64	121.32	13.53	0.000
SPT	2	370.81	185.41	20.68	0.000
WFR	2	120.76	60.38	6.74	0.002
WMT	2	122.99	61.49	6.86	0.002
IP	Pooled				
Error	95	851.59	8.96		
Total	107	2154.94			

B. Estimation of Optimum Response Characteristics

In this section, the optimal values of the material removal rate along with their respective confidence intervals have been predicted. Considering the influence of significant parameters, the optimal set of values of each response characteristic is predicted.

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Table 4: Optimal parameter combination for MRR

Sr. No.	Process Parameters	Optimal level for MRR
1	Pulse width	1.2 µs
2	Time between pulses	5 µs
3	Servo control mean reference voltage	20 volts
4	Short pulse time	0.6 µs
5	Wire feed rate	4m/min
6	Wire mechanical tension	0.5 daN

The estimated mean of the material removal rate is determined utilizing the relation described by [11] and [12-13] as shown in equation 1;

$$\mu_{MRR} = \bar{B}_3 + \bar{C}_1 + \bar{E}_1 + \bar{F}_3 + \bar{G}_1 + \bar{H}_1 - 5\bar{T} \quad (1)$$

Overall mean of MRR

$$\bar{T} = \left[\sum MRR_{(1)} + \sum MRR_{(2)} + \sum MRR_{(3)}\right]/108$$

$$= 18.142\ mm^3/\text{min}$$

Where, MRR_1, MRR_2, and MRR_3 values are taken from the Table 2. The predicted optimal value of MRR is calculated as: $\mu_{MRR} = 28.483 mm^3/min$. The 95 % confidence intervals of confirmation experiments (CI_{CE}) and population (CI_{POP}) are calculated by using the Equations 2 and 3 as rewritten below for ready reference:

$$CI_{CE} = \sqrt{f_\alpha(1, f_e) V_e \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad (2)$$

$$CI_{POP} = \sqrt{\frac{f_\alpha(1, f_e) V_e}{n_{eff}}} \quad (3)$$

$f_\alpha(1, f_e)$ = The F ratio at the confidence level of (1-α) against DOF 1 and error degree of freedom f_e ; $n_{eff} = 8.307$; The N = Total number of experiments = 108; R = Sample size for confirmation experiments = 3; V_e = Error variance = 8.96 (Table 3); f_e = error DOF = 95 (Table 3); $f_{0.05}$ (1, 95) = 3.941 (Tabulated F value);

So $CI_{CE} = \pm 4.0026$, and $CI_{POP} = \pm 2.0610$

Therefore, the predicted confidence interval for confirmation experiments is:

$Mean\mu_{MRR} - CI_{CE} < \mu_{MRR} < Mean\mu_{MRR} + CI_{CE}$; $24.477 < \mu_{MRR} < 32.482$

The 95% confidence interval of the population is:

$Mean\mu_{MRR} - CI_{POP} < \mu_{MRR} < Mean\mu_{MRR} + CI_{POP}$; $26.419 < \mu_{MRR} < 30.541$

V. CONFIRMATION EXPERIMENT

In order to validate the predicted response results, a confirmation experiments was conducted for MRR at optimal levels of the process variables. The results of experiments confirmation for MRR using the optimal machining parameters are shown in Table 5.The average values of the characteristics have been obtained and compared with the predicted values. The predicted value for MRR at optimal parameter setting and the experimental average value is validated by confirmation experiment using MINITAB 15 with percentage error of 3.25%.

Table 5: Experimental observation of MRR using optimal parameter setting

Response	Predicted optimal value	Experimental vales	% Error
Levels	$B_3C_1E_1F_3G_1H_1$	$B_3C_1E_1F_3G_1H_1$	3.25%
MRR (mm^3/min)	---	27.534, 27.168, 28.049	
Average	28.483 mm^3/min	27.584 mm^3/min	

VI. MICROSTRUCTURE ANALYSIS

The microstructure has been studied by the scanning electron micrograph at a magnification of 250-X. Figure 4 depicts the microstructure of the machined surface of Ti-6Al-4V at optimal parametric combination ($B_3C_1E_1F_3G_1H_1$). During Wire-EDM process, the discharged energy produces very high temperatures at the point of the spark, causing a minute part of the sample to melt and vaporize.

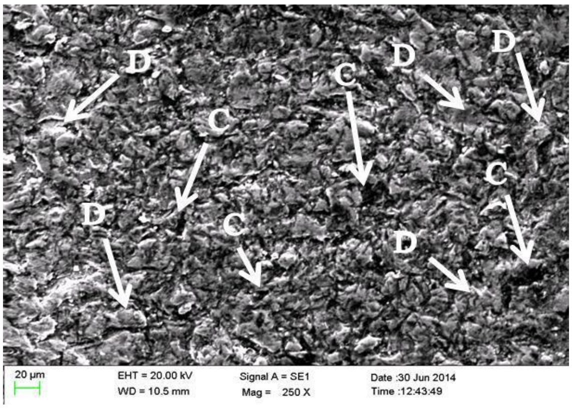

Fig. 4: SEM Micrograph of the Machined Surface

With each discharge, a crater was formed on the machined surface. The surface topography was altered due to significant electrical parameters such as Short pulse time, time between pulses, Pulse width and servo control mean reference voltage. WEDM surface produces the more irregular topography and defects included globules of debris, varying size craters and micro-cracks as shown in figure. The Short pulse time, Pulse width and Servo control mean reference voltage are the most significant parameters which lead to deteriorate the surface texture. When short pulse time was increased the surface texture of the machined surface is composed of varying size of deep craters. These deep and overlapping craters were formed due to successive electrical discharge, intense heat and local melting of work material. Some spherical shape particles were observed due to surface tension of molten material. These effects were turned in poor surface finish.

VII. CONCLUSION

In this investigation, titanium alloy Ti-6Al-4V has machined using Wire-EDM with brass wire and optimal setting of process parameters for material removal rate has been obtained.

1. Short pulse time play a most significant parameter for MRR with brass wire electrode. Increase in short pulse time and pulse width results higher MRR. This is due to the fact that discharge energy increases with increase in SPT and PW. Further with decrease in SCMRV, cutting velocity increases which results higher MRR whereas MRR decrease with increase in WFR and WMT. As TBP increases, the number of discharges within a given period becomes less which leads to decrease in MRR. The process parameters DC, MFR and IP have no such significant effect on MRR.
2. The optimal parametric combination for higher MRR is $B_3C_1E_1F_3G_1H_1$
3. The predicted value for MRR at optimal parameter setting is 28.483mm^3/min and the experimental average value for MRR at optimal parameter setting is 27.584mm^3/min. So the above mathematical prediction for MRR using MINITAB 15 is validated by confirmation experiment as shown above with percentage error 3.27%.

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