International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161
Available at http://inpressco.com/category/ijcet

Research Article

Experimental study and optimization of WEDM of Ti-6Al-4V using Taguchi method

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Accepted 10 Sept 2016, Available online 13 Sept 2016, **Vol.6, No.5 (Oct 2016)**

Abstract

This research work presents influence of process parameters on surface roughness and material removal rate (MRR) while wire electrical discharge machining of titanium grade 5(Ti-6Al-4V). Experiments have been conducted with six process parameters viz., pulse on time, pulse off time, servo voltage, peak current, wire feed rate and wire tension. Taguchi's orthogonal array (L_{27}) was employed for experimental investigation. ANOVA analysis was used to determine most significant factors affecting the machining performance.

Keywords: *Surface roughness, MRR, wire electrical discharge machining, titanium grade 5, Taguchi technique, ANOVA.*

1. Introduction

Titanium is the 22nd element in the periodic table. Titanium grade 5 (Ti-6Al-4V) consists of two phases, aluminium as the alpha stabilizer and vanadium as the beta stabilizer. It possesses excellent properties such as good corrosion resistance in sea water applications, low density, low modulus of elasticity, low thermal coefficient of expansion, non magnetic, good fatigue resistance, exceptional high temperature mechanical properties, excellent cryogenic properties, very short radioactive half life and excellent biocompatibility. It finds wide applications in aerospace industries, biomechanical applications, marine applications, chemical industry and gas turbines. It is also used in structural applications in automotive industries.

There are various problems involved while machining titanium and its alloys conventionally. High cutting temperature is generated at the cutting edge of the tool which results in rapid tool wear. Due to small chip-tool contact area on the rake face and high resistance to deformation at elevated temperature, higher mechanical stresses are produced in the immediate contact area of the cutting edge while machining titanium alloys. As titanium possesses low modulus of elasticity and high dynamic forces are acting during machining, phenomenon of chatters occurs. Due to strong chemical reactivity of titanium with all the tool materials, chips produced during machining of titanium alloys sticks to the cutting edge of the tool. This results in diffusion wear of the tool which increases with increase in temperature (Ezugwu and Wang, 1997).

Wire electrical discharge machining is the most appropriate technique to machine such difficult-to-cut materials. WEDM is an electro thermal process in which material is removed from the work piece due to heat developed from electric sparks in presence of dielectric fluid. Dielectric fluid provides ionization during machining and also it flushes away debris from the machining zone. As there is no contact between wire and work piece during machining, it can cut any electro conductive material regardless of its hardness, toughness and strength. Also, no mechanical stresses are induced during machining. WEDM finds wide applications in aerospace, automotive, tool and die industries where accuracy and surface finish are of prime importance.

Mathematical model for white layer depth was developed during rough cut and finish cut using RSM while WEDM of M2 die steel (Puri and Bhattacharya, 2005). Experimental investigation was carried out on γ-titanium aluminide alloy to study the effect of process parameters on cutting speed, surface finish and dimensional deviation. The process was modeled using additive model and to optimize the response parameters constrained optimization technique and Pareto optimality solution was used (S. Sarkar, *et al,* 2005). Non-dominated sorting genetic algorithm was used for multi-objective optimization of WEDM process. Taguchi's L18 orthogonal array was used to carry out the experiments to study the effect of ignition pulse current, time between two pulses, pulse duration, servo voltage and servo speed on cutting

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velocity and surface finish (Kuriakose and Shunmugam, 2005). WEDM of aluminium reinforced with silicon carbide was performed using Taguchi's L18 orthogonal array. Process parameters considered for the study were pulse peak voltage, pulse on time, pulse off time, peak current, wire feed rate, wire tension and servo voltage while responses were MRR, surface finish, spark gap voltage and gap current. Gauss elimination method was applied to develop mathematical models for the responses (Manna and Bhattacharya, 2006). Genetic algorithm was used for multi-objective optimization of WEDM of D2 die steel. Experiments were designed by applying Taguchi's L27 array to determine effects of discharge current, pulse duration, pulse frequency, wire speed, wire tension and dielectric flow on MRR, surface finish and kerf width (Mahapatra and Patnaik, 2007). Multi-variable regression model and a feed forward back propagation neural network was used to determine relationship between pulse-on time, pulse off time, peak current and capacitance with cutting speed and surface roughness. SEM analysis of machined samples shows increase in size of micro cracks at high energy level (Saha, *et al,* 2008). Optimization of WEDM process parameters were carried out while machining Inconel 718 applying multi-response signal to noise ratio with Taguchi's L9 experimental design. To predict performance characteristics i.e. MRR and surface finish artificial neural network models were developed (Ramkrishnan and Karunamoorthy, 2008). Optimal parameter settings was determined by using hybrid method including response surface methodology and back-propagation neural network integrated with simulated annealing algorithm while machining pure tungsten. Taguchi's L18 orthogonal array for experimental design to study the effect of pulse on time, pulse off time, arc off time, servo voltage, wire feed rate, wire tension and water pressure on MRR, surface finish and corner deviation (Yang *et al,* 2011). Electrical discharge machining of titanium grade 5 was carried out with the help of graphite tool to study the effect of electrical parameters such as current, pulse on time, pulse off time and tool geometry on MRR, surface roughness, tool wear rate and entry and exit deviation. Taguchi's L27 array was used for experimentation and ANOVA was performed to find out the major significant factor affecting the performance characteristics (Sivam *et al*, 2012). Effect of two dielectric fluids viz. distilled water and urea solution on surface roughness was studied while EDM of titanium grade 5 using Cu-TaC composite electrode. Results of the experiment shows that surface roughness obtained by using distilled water was better than using urea solution also higher microhardness was obtained from urea solution (Ndaliman *et al,* 2013). Electro discharge machining of three different grades of titanium (grade 2, grade 5 and grade 6) were carried out under cryogenic condition. Mathematical model for MRR is developed using dimensional analysis and peak current was found to be the most significant factor affecting the MRR (Kumar *et al*, 2014). Influence of process parameters such as pulse on time, pulse off time, peak current, servo voltage, wire feed rate and wire tension on MRR, wire wear ratio and surface roughness while wire electro discharge machining of pure titanium. Experiments were designed using Box-Behnken design and RSM was employed to find out empirical models for output characteristics (Anish kumar *et al*, 2013). Box-Behnken design was used to carry out the experiments on Ti 6-2-4-2 to study the effect of pulse on time, pulse off time, peak current, servo voltage, wire feed rate and wire tension on cutting speed and surface roughness (Garg *et al*, 2014).

This paper explores the wire electrical discharge machining of titanium grade 5. The process parameters selected for the study were pulse on time, pulse off time, servo voltage, peak current, wire feed rate and wire tension. Taguchi's L_{27} orthogonal array was used to carry out the experiments. Performance outputs considered were MRR and surface roughness. ANOVA was performed to find out significant factor affecting the MRR and surface roughness. Mathematical models were developed for MRR and surface roughness by applying regression analysis.

2. Experimental Details

Materials and Methods

The experiments were carried out on wire electrical discharge machine (ELPUSE-40) manufactured by Electronica Machine Tools LTD., India. Brass wire of diameter 0.25 mm was used as a tool electrode. Titanium grade 5 with dimensions 30 mm x 30 mm x 5 mm thickness was taken as a work piece material from which a block of 10 mm x 10 mm x 5 mm was cut with the help of brass wire on WEDM. Chemical composition of titanium grade 5 is shown in Table 1.

Table 1 Chemical composition of Titanium grade 5

Element	Al	V	C	Fe	O	N	H	Ti
%	6.0	4.0	0.08	0.5	0.4	0.05	0.015	89.82

The output characteristics were evaluated in terms of surface roughness and MRR. The surface roughness was measured by using Mitutoyo make SJ-201 surface roughness tester and MRR was calculated by the following equation:

$$\text{MRR}=\frac{\text{Volume of material removed}}{\text{Time taken in min}} \quad (1)$$

Taguchi's L_{27} orthogonal array was used for experimental design. Six process parameters were considered for experimentation viz., pulse on time, pulse off time, servo voltage, peak current, wire feed rate and wire tension. To decide the level of parameters, a large number of experiments were conducted by varying one factor at a time and keeping other parameters constant. Parameters along with their levels are shown in Table 2. Each experimental run was repeated three times thus a total of 81 experiments were carried out to minimize the experimental error.

The "lower-the-better" quality characteristic has been used for calculating signal to noise ratio (S/N) of surface roughness whereas "higher-the better" quality characteristic for MRR.

See Eq. 1 and 2.

$$S/N_{LB} = -10 \log \left[\frac{1}{n}\sum_{1}^{n} Yij^2\right] \quad (1)$$

$$S/N_{HB} = -10 \log \left[\frac{1}{n}\sum_{1}^{n} 1/Yij^2\right] \quad (2)$$

where Yij is the i^{th} experiment at the j^{th} test and n is the total number of repetitions. Statistical analysis was performed by applying MINITAB 16 software. Table 3 represents Taguchi's L_{27} orthogonal array along with the results obtained from the experiments corresponding S/N ratios.

Table 2 Parameters and their levels

Symbol	Machining Parameter	Unit	Level 1	Level 2	Level 3
Ton	Pulse on Time	µs	110	114	118
Toff	Pulse off Time	µs	45	50	55
SV	Servo Voltage	Volts	20	30	40
IP	Peak Current	Amp	170	190	210
W_F	Wire Feed Rate	m/min	1	3	5
W_T	Wire Tension	Gram	2	5	8

Table 3 Taguchi's L_{27} orthogonal array with performance characteristics and respective S/N ratios

Expt. No.	TON	TOFF	SV	IP	WF	WT	Surface Roughness (µm)	S/N ratio	MRR (mm^3/min)	S/N ratio
1.	110	45	20	170	1	2	1.76	-4.8940	21.00	26.4160
2.	110	45	20	170	3	5	1.53	-3.6947	18.26	25.2297
3.	110	45	20	170	5	8	1.46	-3.2694	17.80	25.0082
4.	110	50	30	190	1	2	1.68	-4.4890	20.16	26.0912
5.	110	50	30	190	3	5	1.57	-3.9188	18.76	25.4646
6.	110	50	30	190	5	8	1.45	-3.2096	17.72	24.9707
7.	110	55	40	210	1	2	1.70	-4.5930	20.54	26.2520
8.	110	55	40	210	3	5	1.41	-2.9639	17.50	24.8607
9.	110	55	40	210	5	8	1.35	-2.6505	17.06	24.6412
10.	114	45	30	210	1	5	2.29	-7.1842	28.23	29.0131
11.	114	45	30	210	3	8	2.17	-6.7168	27.69	28.8453
12.	114	45	30	210	5	2	1.80	-5.0896	22.00	26.8510
13.	114	50	40	170	1	5	2.23	-6.9535	28.03	28.9514
14.	114	50	40	170	3	8	1.73	-4.7444	20.60	26.2867
15.	114	50	40	170	5	2	1.91	-5.6219	24.87	27.9119
16.	114	55	20	190	1	5	1.86	-5.3769	23.57	27.4483
17.	114	55	20	190	3	8	2.00	-6.0211	25.70	28.1998
18.	114	55	20	190	5	2	1.88	-5.4837	24.65	27.8360
19.	118	45	40	190	1	8	2.47	-7.8430	32.20	30.1571
20.	118	45	40	190	3	2	1.97	-5.8754	25.37	28.0851
21.	118	45	40	190	5	5	2.37	-7.4834	30.54	29.6964
22.	118	50	20	210	1	8	2.09	-6.3908	27.38	28.7476
23.	118	50	20	210	3	2	2.31	-7.2746	28.40	29.0653
24.	118	50	20	210	5	5	2.20	-6.8354	27.79	28.8777
25.	118	55	30	170	1	8	2.43	-7.7125	31.04	29.8375
26.	118	55	30	170	3	2	2.27	-7.1216	28.00	28.9421
27.	118	55	30	170	5	5	1.62	-4.1736	19.20	25.6684

Table 4 Analysis of variance for surface roughness

Source	DF	Seq SS	Adj MS	F	P	% Contribution
TON	2	1.96347	0.981733	350.62	0.003*	65.08
TOFF	2	0.09389	0.046944	16.77	0.056	3.11
SV	2	0.34629	0.173144	61.84	0.016*	11.48
IP	2	0.36542	0.182711	65.25	0.015*	12.11
WF	2	0.12196	0.060978	21.78	0.044*	4.04
WT	2	0.01307	0.006533	2.33	0.30	0.433
Residual Error	14	0.11277	0.029594	9.57	1.52	3.74
Total	26	3.01687				
S = 0.05292 R-Sq = 99.8% R-Sq(adj) = 97.6%						

*Significant at 95% confidence level

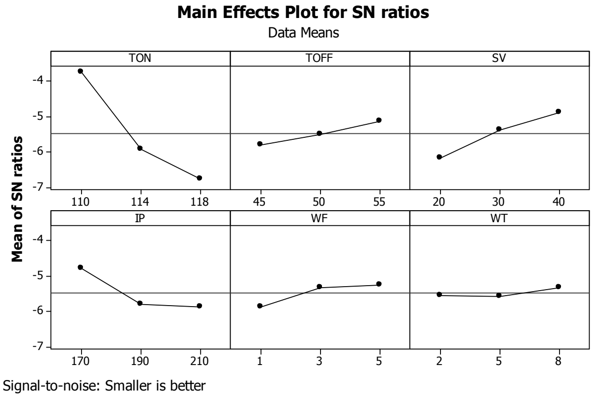

Fig.1 Effect of Process parameters on Surface Roughness

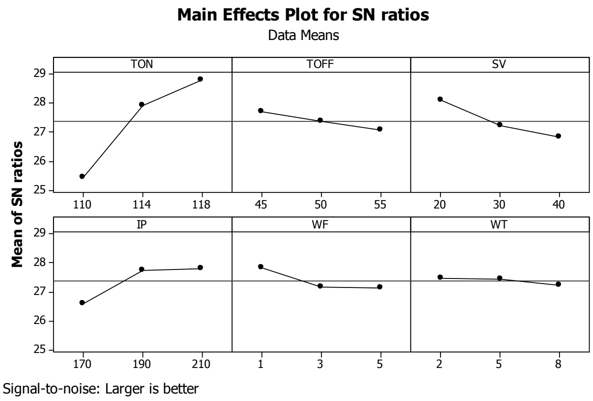

Fig. 2 Effect of Process parameters on MRR

3. Results and Discussion

Effect of Process Parameters on Surface Roughness

From Fig.1, it is found that as pulse on time and peak current increases, poor surface finish is obtained. At high values of pulse on time and peak current more thermal energy is produced which results in deep craters on the machined surface. Higher values of pulse off time indicates amount of time during which current is off. So, at higher values of pulse off time, better surface finish is obtained. Discharge gap gets widened at higher values of servo voltage which leads to better surface finish. At low values of wire feed rate, surface finish becomes poor. There is no significant effect of wire tension on surface finish. Table 4 shows ANOVA analysis on surface roughness.

Effect of Process Parameters on MRR

From Fig.2, it is observed that, with increase in pulse on time and peak current, more amount of material gets melted and evaporated from the surface which results in increase in MRR. As pulse off time, servo voltage and wire feed rate increases, MRR decreases. Wire tension has no effect on MRR. Table 5 shows the ANOVA analysis for MRR.

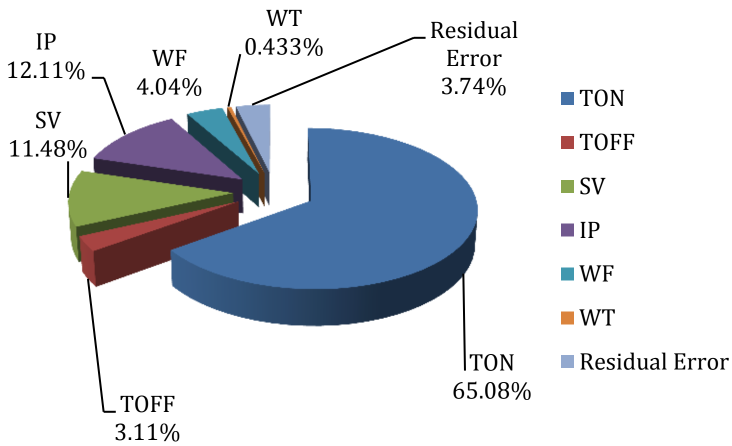

Fig.3 Pie chart showing %age contribution of factors in surface roughness

Table 5 Analysis of variance for MRR

Source	DF	Seq SS	Adj MS	F	P	% Contribution
TON	2	384.496	192.248	128.91	0.008*	66.63
TOFF	2	14.081	7.04	4.72	0.175	2.44
SV	2	54.985	27.492	18.43	0.050*	9.61
IP	2	69.078	34.539	23.16	0.041*	12.08
WF	2	23.714	11.857	7.95	0.112	4.15
WT	2	1.85	0.925	0.62	0.617	0.32
Residual Error	14	28.839	7.955	4.33	1.606	5.04
Total	26	577.042				
S = 1.221 R-Sq = 99.5% R-Sq(adj) = 93.3%						

*Significant at 95% confidence level

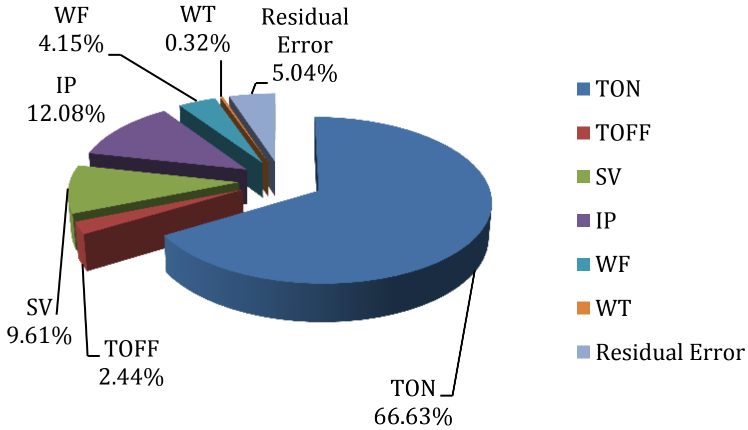

Fig.4 Pie chart showing %age contribution of factors in MRR

Regression Analysis

Regression technique is used to determine mathematical models for surface finish and MRR. It shows the relation between process parameters and output characteristics. Empirical models for surface roughness and MRR is as follows:

Surface Roughness = - 7.21 + 0.0808 TON - 0.0144 TOFF - 0.0137 SV + 0.00628 IP - 0.0389 WF - 0.00778 WT

S = 0.122433 R-Sq = 90.1% R-Sq(adj) = 87.1%

MRR = - 105 + 1.13 TON - 0.176 TOFF - 0.170 SV + 0.0864 IP - 0.520 WF - 0.099 WT

S = 1.88313 R-Sq = 87.7% R-Sq(adj) = 84.0%

Conclusions

In this research work, influence and optimization of six machining parameters on two output characteristics namely surface roughness and MRR is presented using Taguchi's experimental design. To determine prime significant parameter affecting the output characteristics, ANOVA analysis was performed. Mathematical models are developed to establish the interrelationship between process parameters and output characteristics. Following conclusions are drawn from this research work:

1) The most significant factors that affect surface roughness are pulse on time, servo voltage, peak current and wire feed rate.
2) For MRR, the major significant factors are pulse on time, servo voltage and peak current
3) The optimum parameters settings for surface roughness is pulse on time (110), pulse off time (55), servo voltage (40), peak current (170), wire feed rate (5) and wire tension (8).
4) The optimum parameters settings for MRR is pulse on time (118), pulse off time (45), servo voltage (20), peak current (210), wire feed rate (1) and wire tension (2).
5) Empirical models were developed using regression analysis for output characteristics so that we can determine the values of output characteristics at any values of process parameters.

References

E.O. Ezugwu, Z.M. Wang (1997), Titanium alloys and their machinability-a review, *Journal of Materials Processing Technology*, 68, 262-274.

A.B. Puri, B. Bhattacharya (2005),Modeling and analysis of white layer depth in a wire-cut EDM process through response surface methodology, *International Journal of Advanced manufacturing Technology*, 25, 301-307.

S. Sarkar, S. Mitra, B. Bhattacharya (2005), Parametric analysis and optimization of wire electrical discharge machining of γ-titanium aluminide alloy, *Journal of Materials Processing Technology*, 159, 286-294.

Shajan Kuriakose, M.S. Shunmugam (2005), Multi-objective optimization of wire-electro discharge machining process by Non-Dominated Sortng Genetic Algorithm, *Journal of Materials Processing Technology*, 170, 133-141.

A.Manna, B. Bhattacharya (2006), Taguchi and Gauss elimination method: A dual response approach for parametricoptimization of CNC wire cut EDM of PRAlSiCMMC, *International Journal of Advanced manufacturing Technology*, 28, 67-75.

S.S. Mahapatra, Amar Patnaik (2007), Optimization of wire electrical discharge machining (WEDM) process parameters using Taguchi method, *International Journal of Advanced manufacturing Technology*, 34, 911-925.

Probir Saha, Abhijit Singla, Surjya K. Pal, Partha Saha (2008), Soft computing models based prediction of cutting speed and surface roughness in wire electrical discharge machining of tungsten carbide cobalt composite, *International Journal of Advanced manufacturing Technology*, 39, 74-84.

R. Ramkrishnan, L. Karunamoorthy (2008), Modelling and multi-response optimization of Inconel 718 on machining of CNC WEDM process, *Journal of Materials Processing Technology*, 207, 343-349.

R.T. yang, C.J. Tzeng, Y.K. Yang, M.H. Hsieh (2011), Optimization of wire electrical discharge machining process parameters for cutting tungsten, *International Journal of Advanced manufacturing Technology*, DOI 10.1007/s00170-011-3576-z.

S.P. Sivam, A.L. Michalraj, S. Satishkumar, R. Varahamoorthy, D. Dinakaran (2012), Effects of electrical parameters, its interaction and tool geometry in electric discharge machining of titanium grade 5 alloy with graphite tool, *Proceedings of Institution of Mechanical Engineers Part-B Journal of Engineering Manufacture*, 227, 119-131.

M.B. Ndaliman, A.A. Khan, M.Y. Ali (2013), Influence of dielectric fluids on surface properties of electrical discharge

machined titanium alloy, *Proceedings of Institution of Mechanical Engineers Part-B Journal of Engineering Manufacture*, 227, 1310-1316.

S.Kumar, A. Batish, R. Singh, T.P. Singh (2014), A mathematical model to predict material removal rate during electric discharge machining of cryogenically treated titanium alloys, *Proceedings of Institution of Mechanical Engineers Part-B Journal of Engineering Manufacture*, DOI: 10.1177/0954405414527955.

A. Kumar, V. Kumar, J. Kumar (2013), Investigation of machining parameters and surface integrity in wire electric

discharge machining of pure titanium, *Proceedings of Institution of Mechanical Engineers Part-B Journal of Engineering Manufacture*, 227, 972-992.

M.P. Garg, A Jain, G. Bhushan (2014), Multi-objective Optimization of Process Parameters in Wire Electric Discharge Machining of Ti-6-2-4-2 Alloy, *Arabian Journal of Science and Engineering*, DOI 10.1007/s13369-013-0715-x.