VOL. 13, NO. 11, JUNE 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

STATISTICAL AND SURFACE METALLURGICAL STUDY DURING ELECTRIC DISCHARGE MACHINING OF Ti-6Al-4V

Raviraj Shetty[1], Ramamohan Pai[1], Augustine B. V. Barboza[1] and Yashwith Shetty[2]
[1]Department of Aeronautical and Automobile Engineering, Manipal Institute of Technology, Manipal University, Karnataka, India
[2]Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal University, Karnataka, India
E-Mail: rrshetty2@rediffmail.com

ABSTRACT

Titanium alloy (Ti-6Al-4V) is applicable in wide variety of engineering applications due to their attractive and superior properties. However inspite of these properties, they are considered as difficult-to-machine materials because of low heat dissipation, greater tool wear, higher residual stress after machining, severe microstructure alteration and poor surface quality. Hence an attempt has been made to study the statistics and surface metallurgy during electric discharge machining of Ti-6Al-4V in this present paper. The current interest of this paper is to determine the optimum machining conditions for Ti-6Al-4V using statistical tool on Material removal rate (MRR) and Electrode wear (EW) by varying Peak Current (A), Pulse on time (µs), Pulse off time (µs) and spark gap (mm) based on Taguchi's design of experiments and generation of second order model for MRR using Response Surface Methodology. Finally layer formation, surface metallurgy and electrode wear during machining of Ti-6Al-4V has been investigated using Scanning Electron Microscope and Energy dispersive spectrometer.

Keywords: Ti-6Al-4V, Taguchi's design, experiments, response surface methodology, surface metallurgy, material removal rate.

INTRODUCTION

The titanium based alloys comes under a category of advanced materials and are used in variety of applications such as automobile, aerospace, sports and medical applications [1].

EDM is one of the emerging technologies for micro-fabrication methods on which research attempts are being made around the world in the scientific community to explore its potential. [2] Have discussed the machining accuracy of the EDM process and suggested that damage of tool wear results in worsening in the dimensional accuracy. [3] Have reported that improper flushing conditions results in electrode wear. [4] discussed machining input parameters such as EDM current, pulse on-time and flushing pressure certainely effects Material removal, Tool wear and surface roughness on machining metal matrix composites. [5] Suggested that spark gap phenomena are to be more focused while machining using in the EDM. [6] Have investigated that the pulse condition on tool wears, MRR, and machining accuracy. They concluded that voltage and current of the pulse exert strongly to the machining parameters. [7] Have suggested that intense heat generation during EDM process results in white layer formation. [8] Have presented statistical study using Taguchi method. L_{18} orthogonal array has chosen for input process parameters including voltage, current, spark gap and electrode size on the plasma characteristics. [9] Have carried out electrical discharge machining process of Ti–6Al–4V alloy using the Taguchi method. The validation experiments showed there was an improvement in electrode wear ratio, MRR, and surface roughness. [10] Have suggested that EDM process as an inevitable and one of the most popular non-conventional machining processes and has a capability of machining intricate shapes with high dimensional tolerances for machining difficult-to-cut [11] In his research, suggested that increase of pulse off time causes the reduction of tool wear and MRR. [12] in his in his research paper concluded that improved metal removal rate, tool wear rate and surface roughness can be achieved during machining titanium super alloy using copper tool electrode on electric discharge machine (EDM).

Hence this paper concentrates on determining the favorable machining conditions for Ti-6Al-4V on Material removal rate by varying Peak Current (A), Pulse on time (µs), Pulse off time (µs) and spark gap(mm) based on design of experiments using electric discharge machining followed by generation of second order model for MRR using Response Surface Methodology. Finally layer formation, surface metallurgy and electrode wear of machined surface has been investigated using Scanning Electron Microscope and Energy dispersive spectrometer.

METHODOLOGY

Titanium alloy, Ti-6Al-4V as workpiece material having chemical composition has given in Table 1.The titanium round bars were supplied by Baoji Yongshegtai Titanium Industry Co., Ltd China and procured through HAL, Bangalore. The microstructure of the titanium alloy Ti-6Al-4V is shown in Figure-1.

ARPN Journal of Engineering and Applied Sciences

Table-1. Chemical composition (Wt. %) of titanium alloy (Ti-6Al-4V) [18].

Element	Wt (%)
Al	6.1
V	4
Fe	0.16
O	0.11
C	0.02
N	0.01
Y	0.001
H	0.001
Ti	Bal

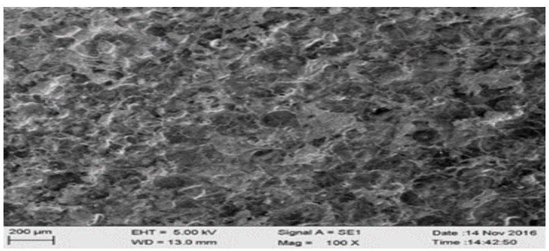


Figure-1. Microstructure of Ti-6Al-4V specimen.

The electric discharge machining experiments of Ti-6Al-4V alloy cylindrical specimen size of 10mm thickness and 75mm diameter(Figure-2) with 10mm diameter copper as electrode material (Figure-2) will be carried out using V3525,VM Engineers electrode discharge machine as shown in Figure-3.

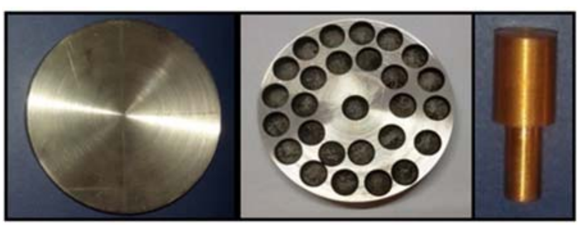


Figure-2. Workpiece material/Electrode material.

Figure-3. Experimental set up.

In the current study for Electric discharge machining operation, four parameters namely, Peak Current (A), Pulse on time (µs), Pulse off time (µs) and Spark gap (mm) were identified. The identified input control factors and their levels are given in Table-2. Output process parameter to be studied was material removal rate, which is measured by weight loss before and after machining using electronic weighting machine Surface metallurgy, layer formation and electrode wear of Electric discharge machined Titanium alloy is analyzed using Scanning electron microscope and Energy dispersive spectrometer.

Table-2. Control factors and levels.

Control factors	Levels		
	1	2	3
Peak Current (A),A	6	9	12
Pulse on time (B), µs	100	300	500
Pulse off time (C), µs	100	200	300
Spark gap (D), mm	0.025	0.05	0.075

DESIGN OF EXPERIMENTS

The analysis is made using the popular software specifically used for design of experiment applications known as MINITAB 15. In any machining experiment, thoughtful changes to process input variables and its effect on process output variables can be achieved using Design of experiments (DOE). Furtherconcrete visualization of process input variables and its effect on process output variables can be obtained using Analysis of Variance (ANOVA).The purpose of ANOVA is to explore which machining parameters strongly affects the quality features. These analyses are carried out for a significant level of 5%, i.e., for a level of confidence of 95% [13-15].

Taguchi's method

At present technology Taguchi techniques has been widely adopted in various conventional machining and non-conventional machining process [13-15]. Taguchi designs has been adopted since it is been proved as an efficient method for designing processes that functionreliably and optimally over a variety of machining conditions.

Response surface methodology

The Response Surface Methodology (RSM) is a tool used for predicting and optimizing the output variables that are influenced by several factors [16-19]. The second order response surface representing the Material removal rate can be expressed as a function of machining parameters such as Peak Current (A),Pulse on time (B), Pulse off time (C) and Spark gap (D). The relationship between the MRR and machining parameters has been expressed as follows: From the observed data for MRR, the response function has been determined in uncoded units as:

VOL. 13, NO. 11, JUNE 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

$$MRR(mm^3/min) = y = \beta o + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_5 A^2 + \beta_6 B^2 + \beta_7 C^2 + \beta_8 D^2 + \beta_9 AB + \beta_{10} AC + \beta_{11} AD + \beta_{12} BC + \beta_{13} BD + \beta_{14} CD + \varepsilon$$

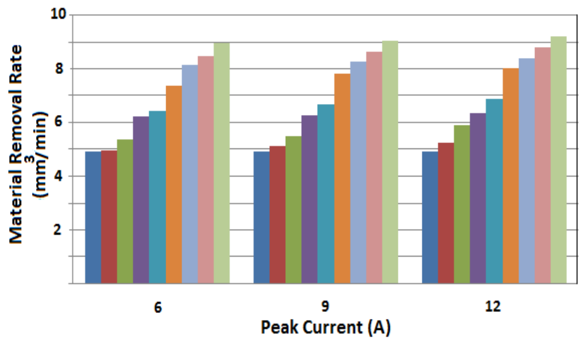
where, β_0, β_1, β_2, ….β_{14} are the regressor coefficients and $\varepsilon$is the random error[16-19].

RESULTS AND DISCUSSIONS

The Material Removal Rate, Tool wear and Layer formation plays a vital role in productivity and quality of Ti-6Al-4V alloy components in any manufacturing industries. Hence to improve the productivity and quality of component, this study mainly focuses on MRR, Tool wear and white layer formation during Electric discharge machining of Ti-6Al-4V alloy.

Material removal rate

The Material removal rate is the most significant factor in Electric Discharge machining of Titanium alloy and is considered as material removed from workpiece under the machining time. The present study is based on Material Removal Rate for Titanium Alloy by Electric Discharge machining under Taguchi's design of experiment.



Conditions	Pulse on Time(µs)	Pulse off Time(µs)	Spark Gap(mm)
	100	100	0.025
	100	200	0.05
	100	300	0.075
	300	100	0.025
	300	200	0.05
	300	300	0.075
	500	100	0.025
	500	200	0.05
	500	300	0.075

Figure-4. Variation of metal removal rate (mm^3/min) with peak current under different machining conditions.

Table-3. Analysis of variance for material removal rate (mm^3/min).

Source	DF	Seq SS	Adj SS	Adj MS	F	P	P(%)
Peak Current (A)	2	89.0451	89.0451	44.5225	631.26	0.000	91.2
Pulse on Time(microseconds)	2	7.1273	7.1273	3.5636	50.53	0.000	7.30
Pulse off Time(microseconds)	2	0.5710	0.5710	0.2855	4.05	0.077	0.58
Spark Gap (mm)	2	0.7582	0.7582	0.3791	5.37	0.046	0.77
Peak Current (A) *Spark Gap(mm)	4	0.0545	0.0545	0.0136	0.19	0.933	0.02
Pulse on Time(microseconds) * Spark Gap(mm)	4	0.1503	0.1503	0.0376	0.53	0.718	0.07
Pulse off Time(microseconds) * Spark Gap(mm)	4	0.0576	0.0576	0.0144	0.20	0.927	0.02
Residual Error	6	0.4232	0.4232	0.0705			
Total	26	98.1872					

Table-4. Response table for material removal rate (mm^3/min).

Level	**Peak current** (A)	**Pulse on time** (microseconds)	**Pulse off time** (microseconds)	**Spark gap** (mm)
1	14.28	16.02	16.75	16.37
2	16.70	16.42	16.39	16.56
3	18.72	17.26	16.56	16.78
Delta	4.44	1.23	0.36	0.41
Rank	1	2	4	3

From the experimental investigations as shown in Figure-4, higher MRR can be achieved with the increase in peak current. It is due to higher discharge energy and higher current density melts & removes the material more

ARPN Journal of Engineering and Applied Sciences

easily. At lower temperature MRR decreases due to adhering of carbon particles to the surface of the tool & forms a layer of carbon.

At higher pulse duration, the discharge energy of electrode is reduced & lower material removal rate is attained. At increase in pulse on time duration leads to fall of MRR due to expansion of plasma channel.

Experiments based on Taguchi's Design of Experiments is used for further analysis of Material removal rate under different machining conditions of Titanium Alloy (Ti-6Al-4V).

It was observed from Main effects Plot(Figure-5) for SN ratios that peak current of 12 amps, Pulse on time(500µs),Pulse off Time (100µs), & spark gap of 0.075 mm would be the ideal condition for maximum Material removal for Ti-6Al-4V alloy.

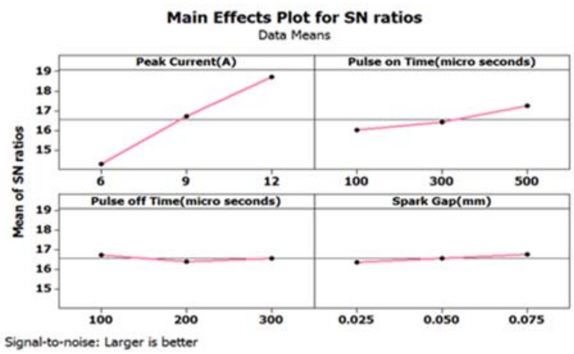


Figure-5. Main effects plot for SN ratio.

Analysis of variance for SN ratio is an easiest technique for identifying percentage of contribution (P%) for examining Material Removal Rate under different machining factors. From the examination Table 3 it is observed for Material Removal Rate peak current(amps) had the maximum contribution of about 91.24%.Hence Peak current is considered to be an important factor, followed by Pulse on time(P=7.30%). Pulse off time, spark gap & interaction effect had a very less contribution on Material Removal Rate during machining of Ti-6Al-4V alloy. Table-4 shows the Response table for material removal rate (mm^3/min)

Layer formation

During Electric Discharge Machining of Titanium alloy, the characterization of surface layer is an important issue to be taken into consideration. This is generalized as white layer and is formed due to re-solidification of melted material, cooling effect of dielectric fluid and high temperature.

Hence it is very much important to analyze the layer formation and to minimize its thickness during Electric Discharge Machining of Ti-6Al-4V alloy. This study mainly deals with Layer formation different Peak Current (A), Pulse on time (µs), Pulse off time (µs) and Spark gap (mm).

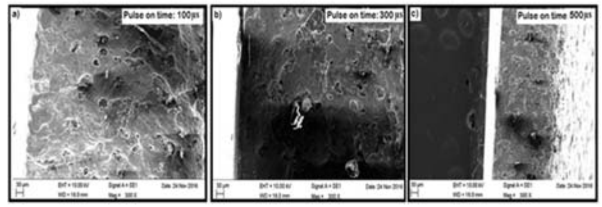


Figure-6. SEM images of white layer formation on machined surface under different pulse on time.

From the experimental investigations Fig 6 it was observed that increase in pulse on time results in increase in white layer thickness. it is due to the fact that increase in pulse on time duration increases the discharge duration time, which leads to melting and vaporization followed by formation of debris re-solidification on the Electric Discharge Machined Surface.

The increase in peak current leads to increase in recast layer thickness. It is due to production of larger craters and melting of more amount of materials from the work surface and solidification from the machined surface. Figure-6 shows the SEM images of white layer formation on machined surface under different pulse on time.

Surface metallurgy

Surface metallurgy of the machined surface layer of Titanium alloy when exposed to high temperature more than 10000˚C and quenching leads to metallurgical alterations such as change in surface and subsurface properties. These changes are mainly influenced by machining condition such as peak current, Pulse duration and spark gap in Electric discharge machining.

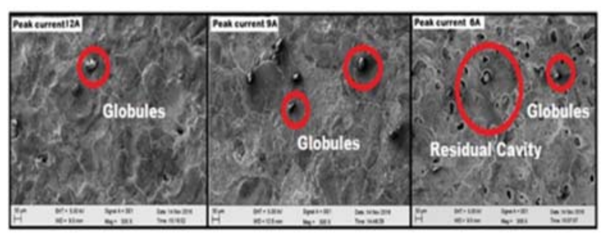


Figure-7. SEM images of EDM surface under different peak current.

Figure-7 shows scanning electron microscope (SEM) images of EDM surface at peak current of 6A, 9A, 12A at constant pulse on time(100µs),pulse off time(300µs) and spark gap of 0.025 mm.

It was observed from the figure that when peak current was 6Amps tiny globules were seen on the machined surface.

This is because when peak current decreases, discharge energy decreases followed by decrease in current density, which results in formation of tiny globules, residual cavity and discharge explosive impact is not too strong enough to destroy the grains.

As the peak current increases from 6 to 12 Amps the single discharge energy increases the amount of heat

VOL. 13, NO. 11, JUNE 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

generated and explosive energy is too large enough to reduce the residual cavity and tiny globules during machining of Titanium alloy.

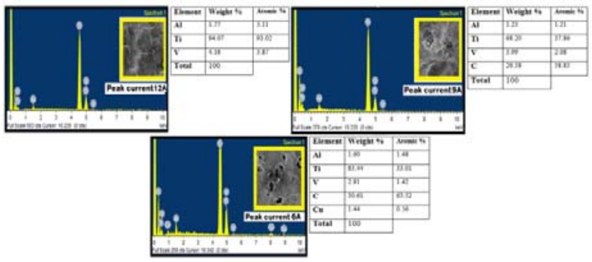


Figure-8. Surface analysis of machined using different peak current.

From the surface analysis of Electric discharge machined Titanium alloy using Energy dispersive spectrometer as shown in Figure-8 it clearly indicates that at peak current of 6A there was carbon deposits of 30.61 % by weight and 63.52 % atomic wt., followed by small amount of copper about 1.44% by weight and 0.56 % atomic wt. This is due to melting and gasification of copper electrode and the influence of thermal stresses. As the peak current increased from 6A to 12A the presence of carbon and copper deposits on machined surface was absolutely negligible due to high energy explosive impact would enhance in destroying the larger grains into smaller grains.

Generation of second order model for material removal rate

Generation of second order model and response surface obtained from response surface methodology representing the Material removal rate can be expressed as a function of machining parameters such as Peak Current (A), Pulse on time (B), Pulse off time (C) and Spark gap (D). Hence the relationship between process output parameter and process input parameters has been expressed as follows:

$$MRR(mm^3/min) = -4.09151 + 2.76296A - 0.00738029B - 0.0333658C - 17.5329D - 0.118501A^2 + 1.55498x\ 10^{-5}B^2 + 8.54491x10^{-5}C^2 - 533.586D^2 - 2.31333x10^{-4}AB - 9.76667x10^{-5}AC - 1.93433AD + 1.19912x10\text{-}5BC - 0.0470900BD - .0297800CD + \varepsilon$$

These response contours can help in estimating MRR at any region of the experimental area. From Fig 9 it is clear from these figures that the MRR increases with the increase of Peak current and decrease in Spark gap.

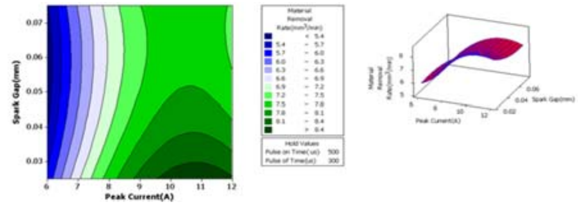


Figure-9. Contour plot and surface plot of MRR at Peak current and Spark gap planes.

Electrode wear

The Electrode wear is considered has most important phenomena has it effects the quality and dimensional accuracy of machined surface. Electrode wear can be categorized as volumetric wear, Corner wear, End wear and Side wear.

From the surface analysis of copper electrode after Electric discharge machining of Titanium alloy using Energy dispersive spectrometer as shown in Figure-10 it clearly indicates that at increase in peak current of 12 Amps, tool wear is affected by the precipitation of carbon from the hydrocarbon dielectric on the electrode surface during sparking. It can also be seen that the rapid wear on the electrode edge was due to the failure of carbon to precipitate at difficult-to-reach regions of the electrode tool.

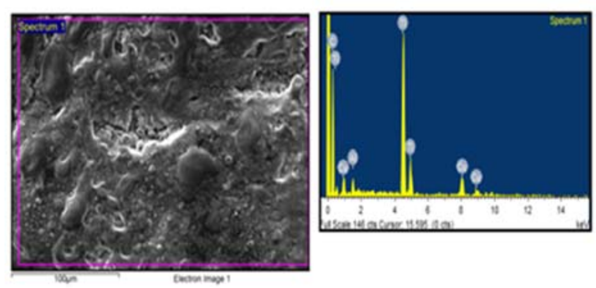


Figure-10. Energy dispersive spectrometer image of the Copper electrode after the erosion of Ti-6Al-4V at 12 A.

CONCLUSIONS

a) From the experimental investigations higher MRR can be achieved with the increase in peak current. It is due to higher discharge energy and higher current density melts & removes the material more easily. At lower temperature MRR decreases due to adhering of carbon particles to the surface of the tool and forms a layer of carbon.
b) At higher pulse duration, the liberation of energy of electrode is reduced hence decrease inmaterial removal rate. At increase in pulse on time duration expansion of plasma channel also leads to decrease in MRR.
c) From Main effects Plot for SN ratios it has been observed that Peak current (12 amps), Pulse on time (500µs), Pulse off Time (100µs) and spark gap of 0.075 mm would be the ideal condition for maximum Material removal for Titanium alloy.

ARPN Journal of Engineering and Applied Sciences

d) From Analysis of Variance for SN ratio examination it is observed that Material Removal Rate peak current(amps) had the maximum contribution of about 91.24%.Hence Peak current is considered to be an important factor, followed by Pulse on time(P=7.30%). Pulse off time, spark gap & interaction effect had a very less contribution on Material Removal Rate during machining of Titanium alloy.
e) From the experimental investigations it was observed that increase in pulse on time results in increase in white layer thickness. it is due to the fact that increase in pulse on time duration increases the discharge duration time, which leads to melting and vaporization followed by formation of debris re-solidification on the Electric Discharge Machined Surface.
f) The increase in peak current leads to increase in recast layer thickness. It is due to production of larger craters & melting of more amount of materials from the work surface & solidification from the machined surface.
g) From the surface analysis of Electric discharge machined Titanium alloy using Energy dispersive spectrometer it clearly indicates that at peak current of 6A there was carbon deposits of 30.61 % by weight and 63.52 % atomic wt, followed by small amount of copper about 1.44% by weight and 0.56 % atomic wt. This is due to melting and gasification of copper electrode and the influence of thermal stresses. As the peak current increased from 6A to 12A the presence of carbon and copper deposits on machined surface was absolutely negligible due to high energy explosive impact would enhance in destroying the larger grains into smaller grains.
h) From the surface analysis of copper electrode after Electric discharge machining of Titanium alloy using energy dispersive spectrometer it clearly indicates that at increase in peak current of 12 Amps, it can also be seen that the rapid wear on the electrode edge was due to the failure of carbon to precipitate at difficult-to-reach regions of the electrode tool.
i) Second order response surface model generated can help in the estimating MRR at any zone of the experimental area.

REFERENCES

[1] I. Abdullin, A. Bagautinov and G. Ibragimov. 1988. Improving surface finish for titanium alloy medical instruments. Biomedical Engineering. 22(2): 48-50.

[2] T. Masuzawa. 2000. A state of art micromachining. CIRP Annals - Manufacturing Technology. 49(2): 473-488.

[3] D.T. Pham., S.S. Dimov, S. Bigot, A. Ivanov, K. Popov. 2004. Micro-EDM-recent developments and research issues. Journal of Materials Processing Technology. 149: 50-57.

[4] P. Narender Singh., K. Raghukandan, M. Rathinasabapathi, B.C. Pai. 2004. Electric discharge machining of Al–10%SiCP as-cast metal matrix composites. Journal of Materials Processing Technology. 155-156: 1653-1657.

[5] Kunieda M., B. Lauwers, K. P. Rajurkar, B. M. Schumacher. 2005. Advancing EDM through Fundamental Insight into the Process. CIRP Annals - Manufacturing Technology. 54(2): 64-87.

[6] Seong Min Son, HanSeok Lim, A.S. Kumar, M. Rahman. 2007. Influences of pulsed power condition on the machining properties in micro EDM. Journal of Materials Processing Technology. 190: 73-76.

[7] B. Bhattacharya, A.K. Khanra, B.R. Sarkar, L.C. Pathak, M.M. Godkhindi. 2007. Performance of ZrB2–Cu composite as an EDM electrode. Journal of Materials Processing Technology. 183: 122-126.

[8] Nagahanumaiaha, Janakarajan Ramkumar, Nick Glumac, Shiv G. Kapoor, Richard E. DeVor. 2009. Characterization of plasma in micro-EDM discharge using optical spectroscopy. Journal of Manufacturing Processes. 11: 82-87.

[9] J.Y. Kao, C.C. Tsao, S.S. Wang & C.Y. Hsu. 2010. Optimization of the EDM parameters on machining Ti-6Al-4V with multiple quality characteristics. International journal of advanced manufacturing Technology. 47(1-4): 395-402.

[10] M.P. Jahan, M. Rahman, Y.S. Wong. 2011. A review on the conventional and micro-electro discharge machining of tungsten carbide, International Journal of Machine Tools & Manufacture, Vol. 51, pp.837–858.

[11] S. Daneshmand, E.K. Farahmand, N.A.A Lotfi and G.M. Mortazarvi. 2013. Experimental investigations into Electro Discharge Machining of NiTi Shape Memory Alloys using rotational tool. International Journal of Electrochemical science. 8: 7484-7497.

[12] J. Laxman and Dr. Guru Raj K. 2014. Optimization of EDM process parameters on Titanium Super Alloy Based on Grey Relational analysis. International Journal of Engineering Research. pp. 344-348.

ARPN Journal of Engineering and Applied Sciences

[13] M.S. Phadke. 1989. Quality engineering using robust design. Englewood Cliffs, NJ: Prentice-Hall;

[14] P.J. Ross, Taguchi. 2005. Techniques for Quality Engineering. McGraw-Hill, New York, 1996.

[15] D.C. Montgomery. Design and analysis of experiments. New York: John Wiley and Sons.

[16] R.Shetty, RB Pai, SS Rao, V Kamath. 2008. Study on surface roughness minimization in turning of DRACs using surface roughness methodology and Taguchi under pressured steam jet approach. ARPN Journal of Engineering and Applied Sciences. 3(1): 59-67.

[17] R. Shetty, RB Pai, SS Rao, V Kamath. 2008. Machinability study on discontinuously reinforced aluminium composites (DRACs) using response surface methodology and Taguchi's design of experiments under dry cutting condition. Maejo International Journal of Science and Technology. 2(01): 227-239.

[18] P.K. Shetty, R. Shetty, D. Shetty, N.F. Rehaman, T.K Jose. 2014. Machinability study on dry drilling of titanium alloy Ti-6Al-4V using L9 orthoganal array. Procedia Materials Science. 5: 2605-2614.

[19] R. Shetty, R. Pai, S.S. Rao. 2008. Tribological studies on discontinuously reinforced aluminium composites based on the orthogonal arrays. ARPN Journal of Engineering and Applied Sciences. 3(1): 94-92.