EXPERIMENTAL INVESTIGATIONS ON ORBITAL ELECTRO DISCHARGE MACHINING OF INCONEL 718 USING TAGUCHI TECHNIQUE

Harshit Dave[1], Keyur Desai [2], Harit Raval [3]

[1, 2, 3] Sardar Vallabhbhai National Institute of Technology, Department of Mechanical Engineering, Ichchhanath, Surat – 395007, Gujarat, India

Corresponding author: Harshit K. Dave, harshitkumar@yahoo.com

Abstract: In present study, experimental investigation is carried out on electro discharge machining process under orbital tool movement. Tool electrode is actuated along a helical path through simultaneous movement of X-Y axis along with Z axis. Attempt has been made to study the effect of orbital parameters along with machine parameters on response characteristics viz. material removal rate (MRR) and surface roughness (Ra) while machining Inconel 718. The Taguchi experimental design is applied to find out the optimal combination of process parameters to maximize the material removal rate as well as minimize surface roughness. Analysis of Variance (ANOVA) is performed and Signal-to-noise(S/N) ratio is determined to know the level of significance of the process parameters on the response characteristics. Current and Orbital Radius are found to be the significant parameters. The results obtained are critically discussed and have been confirmed experimentally at 95% confidence level. Further, the effect of significant parameters on surface conditions is studied with scanning electron microscopy.
Key words: EDM, Orbital tool movement, orbital radius, Inconel 718, Taguchi technique, S/N ratio

1. INTRODUCTION

One of the most extensively used non conventional machining processes is electro discharge machining process which is particularly advantageous in manufacturing of moulds, dies, automotive, aerospace and surgical components owing to its unique feature of using thermal energy to machine electrically conductive parts regardless of its hardness (Ho & Newman, 2003). The material erosion mechanism primarily makes use of electrical energy and converts it into thermal energy, through a series of discrete electrical discharges occurring between the electrode and the work piece immersed in a dielectric fluid (Tsai et al., 2003).

Research in the area of orbital tool actuation during electro discharge machining process has been reported where it is possible to decouple the size of the electrode from the size of the feature to be machined. During orbital EDM process, an electrode that is significantly smaller than the cavity to be generated is actuated on a path that will articulate its outer surface on a trajectory equal to the shape of the hole. Thus, it is possible to use a standard electrode to drill a wide range of holes while the increased clearance between the hole and the electrode helps getting the dielectric fluid to the bottom of the hole. The use of a small size of standard electrodes instead of matched electrodes for every single whole size drastically reduces tooling efforts (Guitrau, 1997).

Few researchers have carried out study of the effect of orbital tool movement on various response characteristics and found the process to be advantageous (Rajurkar & Royo, 1988; 1989; Bamberg et al, 2005). After carefully studying the available literature, it is found that there are few published works on investigation on orbital tool motion for minimization of machining time and improving surface finish. Most of the reported literature is based on comparison of orbital EDM with conventional sinker EDM. These suggest the capabilities of orbital motion but do not provide any information on optimum selection of orbital motion parameters with other machine parameters. Recently, El-Taweel and Hewidy (2009) have worked on two orbital motion strategies viz. helical path strategy and spiral path strategy. They found that orbital motion in helical path gives relatively better results as compared to spiral path. However, they have considered constant values of all machine parameters like current, voltage, pulse duration, etc. Hence, it is not possible to arrive at any conclusion on the effect of orbital motion if there is variation in any of the machine parameters. Wide setting ranges of all machine parameters are available in modern EDM machine and specific ranges are used for specific applications. Hence, it is very important to study the combined effect of orbital parameters with the machine parameters so that useful database can be created which can be of immense help for end users in the practical definition of orbital EDM process in order to have proper adjustment of machining time and surface quality.

In recent times, nickel based alloys like Inconel 718 are gaining importance in making of gas turbines, space crafts, rocket motors, nuclear reactors etc.

These classes of materials, being strong, light weight and aesthetic in appearance represent an excellent choice specifically for construction of aerospace components. However, nickel based super alloys are among the work materials with the lowest machinability properties. They are specifically designed to retain high strength at elevated temperatures due to which higher cutting forces are encountered as compared to steel. The low thermal conductivity of nickel alloys give rise to high temperatures as compared to steel material is another issue. These lead to difficulty in machining of these alloys using conventional techniques (Shaw, 1997). As a result, EDM process becomes a natural choice for machining of nickel based super alloys.

In present work, it is attempted to carry out experimental investigations on machining of Inconel 718 material using electro discharge machining process under orbital tool actuation. It is intended to optimize orbital parameters viz. orbital radius and orbital speed along with machine parameters. Taguchi approach is utilized for experimental design. Results obtained are critically discussed and analyzed.

2. EXPERIMENTAL PLAN AND PROCEDURE

2.1 Machine Tool

Joemars make ZNC EDM which has the provision for actuating tool in lateral (X-Y) plane along with Z-axis is used in present study. The machine has the capability to control Z axis movement with precision upto 1 μm. The orbital mechanism can control X and Y axis movement independently with same precision of 1 μm. Thus, there is simultaneous movement of all three axis as a result of which the electrode orbits along a helical path. The machine tool is depicted in figure 1.

Fig. 1. Electro Discharge Machine with orbital set up

2.2 Workpiece and tool electrode

Inconel 718 is taken as work piece material and electrolyte copper is taken as electrode material. The chemical composition of Inconel 718 is given in table 1.

Table 1. Chemical Composition of Inconel 718

C	0.03	Ni	52.133
Cr	17.429	Nb	5.042
Co	0.236	Ti	1.141
Cu	0.031	P	0.005
Fe	19.903	S	0.004
Mn	0.046	Si	0.117
Mo	2.833		

The work piece is cut into the size of 13x13x10 mm. Two work pieces are clamped together as shown in figure 2 and hole is drilled at the interface of two polished surfaces of the work piece. The split work piece enables easy separation after machining and hence opens the internal surface for further study.

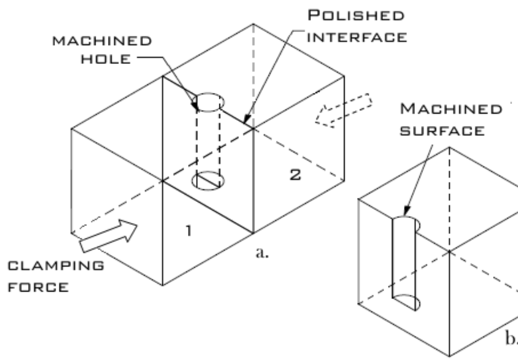


Fig. 2. Work piece design and method of application

Copper electrode is fabricated to a length of 20mm with varying diameter of 5, 6, 7, 8, and 9mm. Each tool with a specific diameter is given orbital movement at an orbital radius so as to generate a circular hole of 10mm diameter up to a depth of 10mm. Commercially available dielectric fluid is used during the experiments.

2.3 Parameter selection

The process parameters chosen for the present experiment are: (A) Orbital Radius R_o, (B) Orbital Speed S_o, (C) Current I, (D) Gap Voltage V_g, (E) Pulse ON time t_{on} and (F) Duty Factor DF. These parameters were selected because they can potentially affect MRR and surface roughness. The input parameters and the number of levels of each of these parameters are presented in table 2.

2.4 Response selection

In present investigation, it is aimed to study the effect of orbital tool actuation during EDM on material removal rate (MRR) and Surface roughness (Ra).

Table 2. Input Parameters and their level

Parameter	Unit	Level 1	Level 2	Level 3	Level 4	Level 5
Orbital Radius R_o	mm	0.5	1.0	1.5	2.0	2.5
Orbital Speed S_o	mm/s	0.05	0.07	0.09	0.11	0.13
Current I	A	9	13	17	21	28
Gap Voltage V_g	V	40	55	70	85	100
Pulse ON time t_{on}	µs	93	165	240	315	385
Duty Factor DF	--	0.4	0.5	0.6	0.7	0.8

MRR (mm^3/min) is calculated by weight difference of the work piece and tool electrode respectively before and after machining using a precision weighing machine (maximum capacity = 300g, least count=1mg).

The equation used for calculating MRR is as under:

$$MRR = \frac{(W_{w_i} - W_{w_f})}{\rho_w \times t} \quad (1)$$

where: W_{wi} is the initial weight of work piece; W_{wf} is the final weight of work piece; ρ_w and ρ_t are density (g/mm^3) of work piece and tool respectively and t is the machining time (min).

The objective of this experimental work is to determine the machining conditions required to achieve (a) maximum Material Removal Rate (MRR) (b) minimum surface roughness under orbital tool motion in EDM process. Therefore, quality characteristic of larger-the-better (LB) for MRR and smaller-the- better (SB) for surface roughness is implemented in this study. The S/N ratio (η) is calculated using the equations given as under:

For LB characteristics:

$$\eta_i = -10\log_{10}\left(\frac{1}{n}\sum_{j=1}^{n}\frac{1}{y_{ij}^2}\right) \quad (2)$$

For SB characteristics:

$$\eta_i = -10\log_{10}\left(\frac{1}{n}\sum_{j=1}^{n}y_{ij}^2\right) \quad (3)$$

where y_{ij} is the response of i^{th} quality characteristics at j^{th} experimental run and n is the total number of repetition of a run.

2.5 Orthogonal array selection

In present study, experiments have been designed using Taguchi approach. In comparison with a traditional full factorial design of experiments, Taguchi approach provides a significant reduction in the number of experiments runs, thereby speeding up the experimental process (Phadke, 1989, Taguchi et al, 2004) and reducing the total cost incurred. In present study, six parameters have been included and each parameter is varied at 5 levels. The Taguchi orthogonal array suitable for 6 factors each at 5 levels is L25 where it is required to perform 25 experimental runs. The layout of L25 orthogonal array for present study is depicted in table 3.

All experiments trials have been randomized to minimize the bias from both between experiments and within experiment error and have been replicated twice. When the first machining spark initiated, a stopwatch was activated and time elapsed to reach the predefined machining depth of 10mm along Z-axis was recorded. The machining time so noted to achieve the machining depth has been used to calculate MRR using equation (1). S/N ratio (η) for material removal rate and surface roughness are calculated based on equations (3) and (4) and are listed in table 2.

3 RESULT DISCUSSIONS

3.1 Analysis of MRR

It the value of S/N ratio (η_{ij}) is higher than it shows a better performance. The average values of S/N ratios of MRR for each parameter at all 5 levels are calculated. These are plotted as shown in figure 3.

The analysis of S/N ratio reveals that the optimal performance for the MRR can be obtained at orbital radius 0,5mm (level 1), orbital speed 0.09mm/s (level 3), current 28A (level 5), gap voltage 70V (level 3), pulse ON time 315 µs (level 4) and duty factor of 0.7 (level 4). Further, ANOVA is carried out which provides useful information about the significance of each parameter. The ANOVA result for S/N data of MRR is summarized in table 4.

It is worth noting here that the suggested optimal value of orbital speed is at level 3. However, there is very minor difference between the mean value of S/N ratio at level 3 and that at level 1 as well as level 5. This means that these results can vary in a new set of experiments. Further, itIt can be, further, noted that orbital speed may have very minor effect on the MRR as is found from ANOVA.

It can be seen that best MRR is obtained at minimum orbital radius which is in agreement with the results of El Taweel and Hewidy (2009). As the orbital radius increases, the free gap available between the tool electrode and work piece also increases resulting in lesser sparking on other parts of tool work piece interface. As a result, spark gar in such area and hence the gap voltage becomes insignificant which is evident from the ANOVA table also. It can be, further, seen from table 4 that current is the highest significant parameter during orbital EDM process.

Table 3. Experimental plan using L25 orthogonal array & S/N ratio values

Exp. No.	A	B	C	D	E	F	S/N ratio (η) (dB)	
	Orbital Radius, R_o, (mm)	Orbital Speed S_o, (mm/s)	Current *I*, (A)	Gap Voltage, V_g (V)	Pulse ON time t_{on}, (μs)	Duty Factor *DF*	MRR	Ra
1	1	1	1	1	1	1	22.002	-13.3864
2	1	2	2	2	2	2	27.2148	-14.8195
3	1	3	3	3	3	3	31.042	-16.7103
4	1	4	4	4	4	4	32.957	-16.4798
5	1	5	5	5	5	5	35.4554	-17.6782
6	2	1	2	3	4	5	27.3941	-14.7174
7	2	2	3	4	5	1	26.3298	-15.4039
8	2	3	4	5	1	2	29.2548	-16.1453
9	2	4	5	1	2	3	29.0299	-18.3971
10	2	5	1	2	3	4	23.7371	-13.878
11	3	1	3	5	2	4	27.01	-16.7218
12	3	2	4	1	3	5	26.4916	-17.6304
13	3	3	5	2	4	1	29.2357	-19.5206
14	3	4	1	3	5	2	19.6554	-13.7348
15	3	5	2	4	1	3	23.0774	-14.1769
16	4	1	4	2	5	3	27.8141	-18.2972
17	4	2	5	3	1	4	30.0293	-18.0653
18	4	3	1	4	2	5	21.1209	-13.652
19	4	4	2	5	3	1	21.4832	-15.8528
20	4	5	3	1	4	2	24.7805	-16.4384
21	5	1	5	4	3	2	26.3695	-19.3586
22	5	2	1	5	4	3	17.8244	-14.3126
23	5	3	2	1	5	4	21.5131	-16.035
24	5	4	3	2	1	5	21.1235	-15.484
25	5	5	4	3	2	1	23.1567	-17.1131

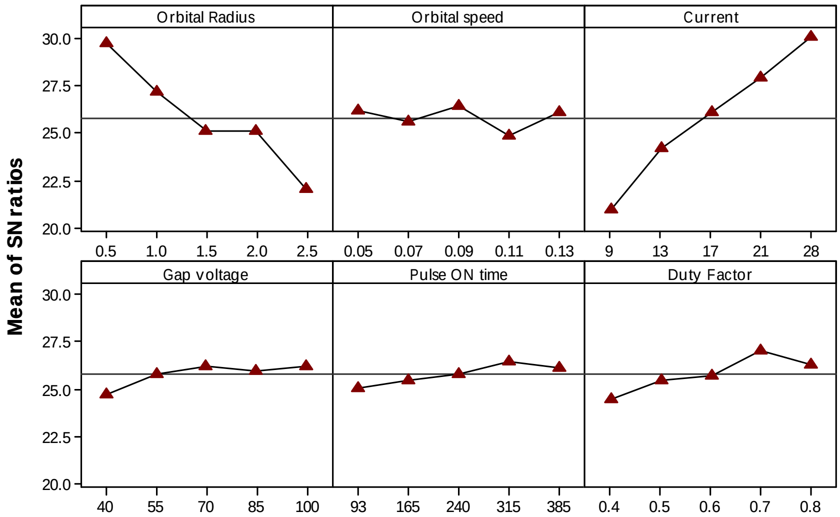


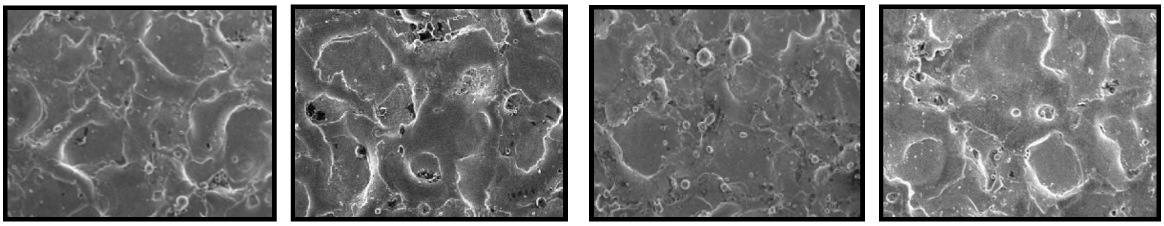
Fig. 3. Main effect plot for MRR

Table 4. ANOVA for MRR

Factor	Degree of Freedom	Sum of Squares	Mean Square	F	P value	%P
A: Orbital radius	4	164.128	41.032	24.011	<0.001	**36.36**
B: Orbital speed	4	7.562#	1.8905	--	--	1.68
C: Current	4	247.791	61.9478	36.25	0.000	**54.89**
D: Gap voltage	4	7.381#	1.8453	--	--	1.64
E: Pulse ON	4	5.564#	1.391	--	--	1.23
F: Duty Factor	4	18.973	3.7946	2.22	0.13	4.2
Total	24	451.399	18.8083			
Pooled error	12	20.507	1.7089			100

# indicates the values of SS added together to estimate the pooled error SS. F ratio is calculated by using pooled error MS.

The percent contribution of the machining parameters on the MRR shown in table 3 reveals that current and orbital radius have highest effect on MRR during orbital EDM process. Hence, these are the most significant parameters in orbital EDM. The effect of current and orbital radius can be understood from the SEM micro graphs shown in figure 4. It is known that the effective spark energy available at the machining area is directly proportional to the current. If the current decreases, the effective energy available at tool – workpiece combination also decreases. Hence, the size of craters formed gets reduced which results into reduction in MRR. Similarly, it can also be seen that irrespective of current value, as the orbital radius increases, the crater size gets reduced resulting into lesser MRR. These observations match with the authors' preliminary observations on AISI 304 reported earlier in Dave et al., 2011.



(a) I = 28A, r_o = 0,5mm (b) I = 9A, r_o = 0,5mm (c) I = 28A, r_o = 2,5mm (d) I = 9A, r_o = 2,5mm

Fig. 4. SEM micrographs showing effect of current and orbital radius on MRR of Inconel 718 (Magnification: 180X)

3.2 Analysis of Surface roughness

The values of S/N ratios of surface roughness (Ra) for each parameter at all 5 levels are calculated and plotted in figure 5. The analysis of S/N ratio reveals that the optimal performance for the surface roughness can be obtained at orbital radius 1.0 mm (level 2), orbital speed 0.13 mm/s (level 5), current 9A (level 1), gap voltage 85V (level 4), pulse ON time 93 µs (level 1) and duty factor of 0.8 (level 5). ANOVA is performed to determine which factor significantly affected surface roughness. The ANOVA result for S/N data of surface roughness (Ra) is given in Table 5. It can be noted from ANOVA table that current is the most significant process parameter on surface roughness of the cavity machined on Inconel 718 under orbital electro discharge machining of Inconel 718. The other significant parameter is pulse ON time but its effect is very less as compared to current.

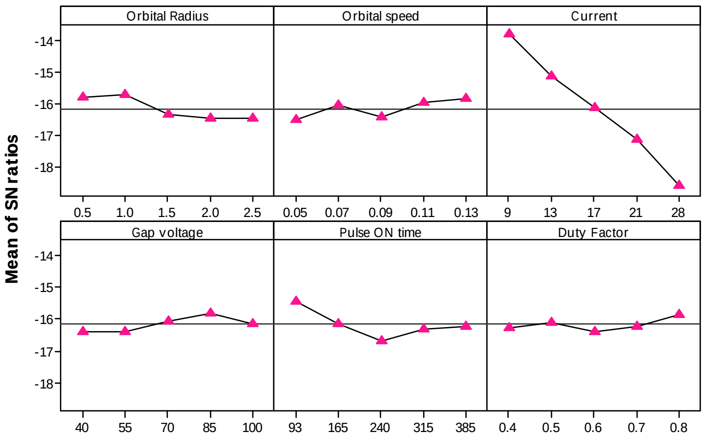


Fig. 5. Main effect plot for Ra

Table 5. ANOVA for Ra

Factor	Degree of Freedom	Sum of Squares	Mean Square	F	P value	%P
A: Orbital radius	4	2.7149	0.6787	2.27	0.122	3.47
B: Orbital speed	4	1.5533#	0.3883	--	--	1.98
C: Current	4	68.0244	17.0061	56.88	0.000	**86.84**
D: Gap voltage	4	1.1656#	0.2914	--	--	1.48
E: Pulse ON	4	4.0085	1.0021	3.35	0.045	**5.12**
F: Duty Factor	4	0.8688#	0.2172	--	--	1.11
Total	24	78.3354				100
Pooled error	12	3.5877	0.299			

# indicates the values of SS added together to estimate the pooled error SS. F ratio is calculated by using pooled error MS.

Further, it can be seen that the effect of orbital radius and orbital speed are very less on surface roughness. Thus, it can be said that orbital parameters do not produce any adverse effect on the surface roughness of the machined cavity. Further, as orbital radius increases, there is very small reduction in surface roughness which is in line with the findings by various researchers (El Taweel & Hewidy, 2009; Bamberg & Sumet, 2009).

4. CONFIRMATION TESTS

The taguchi design of experiments is based on a simple additive model where only the effect of each factor on the output is analyzed and interactions between factors are generally avoided (Phadke, 1989). If the additive model holds true, the value of η_{opt}(dB) under optimum conditions is given by equation 4 (Phadke, 1989).

$$\eta_{opt} = \eta_m + \sum_{j=1}^{k} \left(\eta_j - \eta_m \right) \quad (4)$$

where η_m is the overall mean SN ratio, η_j is the mean SN ratio at optimum level, and k is the number of control factors that affect the response.
For the optimal setting of parameters for MRR, the value obtained for the SN ratio using equation (4) at the optimal settings is 33.9542 dB and the SN ratio obtained from the confirmation experiments is 34.13 dB. Similarly for the optimal setting of parameters for Ra, the SN ratio predicted for the optimal setting is -13.084 dB and the value obtained from the confirmation experimental results at this setting is -13.9868 dB. It can be seen that in both of these cases, the predicted value is very close to the measured value. The error in the predicted and confirmed values of S/N ratio for MRR and Ra is found to be 0.52% and -6.9% respectively which are in acceptable range. Thus, it can be said that the optimal combination yields good results.

5. CONCLUSIONS

Experimental investigation has been carried out to study the effect of orbital parameters viz. orbital radius and orbital speed on Inconel 718 material during EDM process by carrying out experiments based on Taguchi approach. It is found that orbital tool actuation can effectively carry out machining of Inconel 718 which is otherwise difficult to machine material by conventional means. The significance of parameters involved during the process has been checked through ANOVA technique. The following important conclusions have been made during the present study:
(1) It is found that orbital radius and current significantly affect the MRR while current and pulse on time are significant parameters for surface roughness.
(2) As orbital radius increases, there is reduction in MRR and rise in surface roughness. Thus, it can be seen that orbital process is more effective at lower settings of orbital radius.
(3) The results have been confirmed experimentally at 95% confidence level and it is found that the error between predicted S/N ratio and confirmed S/N ratio for MRR and surface roughness are 0.52% and -6.9%.

ACKNOWLEDGEMENT

The authors are thankful to Department of Science & Technology, Government of India for financial support for this research work through the research grant vides grant permission SR/S3/MERC-0044/2010(G). Further, the guidance provided by Prof. P. R. Apte, IIT Bombay in designing the experimental plan is acknowledged with sincere thanks.

6. REFERENCES

1. Bamberg, E., Sumet, H., Jorgensen, J. D., (2005). *Flexural micro EDM head for increased productivity of micro holes*, Proceedings of ASPE, Alex Shon (Ed.) pp. 82-85, Norfolk, VA.
2. Bamberg, E., Sumet, H., (2009). *Orbital electrode actuation to improve efficiency of drilling micro holes by micro EDM*, Journal of Materials Processing Technology, 209(4), pp. 1826-1834.
3. Dave, H. K., Desai, K. P., Raval, H. K., (2011). *Effect of orbital tool movement on material removal rate during electro discharge machining*, Proceedings of Int. Conf. on Adv. & Trends in Engg. Materials and their applications, Y. M. Haddad (Ed), pp. 365-370, Montreal, Canada.
4. El-Taweel, T. A., Hewidy, M. S., (2009). *Enhancing the performance of electro discharge machining via various planetary modes*, International Journal of Machining & Machinability of Materials, 5(2/3), pp. 308-320.
5. Guitrau, E. B., (1997). *The EDM Handbook*, pp. 71–82, Hanser Gardner, Cincinnati, OH.
6. Ho, K. H., Newman, S. T., (2003). *State of the art Electro Discharge Machining (EDM)*, International Journal of Machine Tools and Manufacture, 43(13), pp. 1287-1300.
7. Phadke, M. S., (1989). *Quality Engineering using robust design*, PTR Prentice Hall, New Jersey, pp. 67-92.
8. Rajurkar, K. P., Royo, G. F., (1988). *Improvement in EDM performance by R. F. control and orbital motion*, ASME journal of Production Engineering Division, 34, pp. 51-62.
9. Rajurkar, K. P., Royo, G. F., (1989). *Effect of R. F. Control and orbital motion on Surface integrity of EDM Components*, Journal of Mechanical Working Technology, 20, pp. 341-352.
10. Shaw, M.C., (1997). *Metal Cutting Principles*, Clarendon, Oxford, pp. 1-25.
11. Taguchi, G., Chowdhury, S., Wu, Y., (2004). *Taguchi's Quality Engineering Handbook*, John Wiley, New Jersey, pp. 515-596.
12. Tsai, H. C., Yan, B. H., Huang, F. Y., (2003). *EDM performance of Cr/Cu based composite electrodes*, International Journal of Machine Tools and Manufacture, 43 (3), pp. 245-252.

Received: December 5, 2011 / Accepted: June 8, 2012 / Paper available online: June 10, 2012 © International Journal of Modern Manufacturing Technologies.