Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 174 (2017) 53 – 59

Procedia Engineering

www.elsevier.com/locate/procedia

2016 Global Congress on Manufacturing and Management

Performance Evaluation of Electrode Materials in Electric Discharge Deep Hole Drilling of Inconel 718 Superalloy

P Kuppan*, S Narayanan, R Oyyaravelu, A S S Balan

Department of Manufacturing Engineering, School of Mechanical Engineering,
VIT University, Vellore 632014, India

Abstract

In the present study, electric discharge deep hole drilling of Inconel 718 was experimented with three different commercial tube electrodes viz., copper, copper-tungsten and graphite. The pertinent process parameters selected for the study were peak current, pulse on-time, duty factor and electrode rotational speed. The machining performance was investigated by analysing Material Removal Rate (MRR), Electrode Wear Ratio (EWR) and Surface Roughness (SR). The experiments were planned according to Response Surface Method (RSM) and Central Composite Design (CCD). Through holes of diameter around 3.0 mm and 25 mm depth were drilled. Experimental data was fitted and regression analysis was done. The experimental results indicated that copper electrode outperformed copper-tungsten and graphite electrodes with regard to MRR and SR. Further, the EWR was high in copper electrode followed by copper-tungsten and graphite electrodes. Among the three electrode materials tested, copper is the best choice of electrode material with respect to high MRR and low SR.

Peer-review under responsibility of the organizing committee of the 13th Global Congress on Manufacturing and Management

Keywords: *EDM; Deep hole drilling; Inconel 718; copper; copper tungsten; graphite; material removal rate; electrode wear ratio;* surface roughness.

---

*Corresponding author: P. Kuppan. Tel.: +91 416-2202228; fax: +91 416-2243092.
E-mail address: pkuppan@vit.ac.in.

Peer-review under responsibility of the organizing committee of the 13th Global Congress on Manufacturing and Management
doi:10.1016/j.proeng.2017.01.141

1. Introduction

The electrical discharge drilling (EDD) is an extremely prominent machining process for small deep hole drilling among the newly developed non-traditional machining techniques. The advantages of EDD include: Simple tooling and its capability of drilling multiple holes simultaneously, absence of burrs, ability to drill on angled surfaces and tough superalloys. The EDD process, which utilizes thermal effect rather than mechanical force to remove material is highly suitable for machining of superalloys, which have the highest hardness in reinforcement. The EDD is used for creating the long cooling channels in aero-engine gas-path components such as turbine blades, guide vanes, after burners and castings [1].

Making of small holes by EDD in aerospace industries is a common process. Some of the published past works on EDD of superalloy, specifically nickel based alloys are presented here. During machining of nickel-based alloy with graphite electrode, Wang et al. [2] observed that the material removal rate is significantly influenced by pulse on-time. Yilmaz and Okka [3] compared the performance of single and multi-channel electrodes during electric discharge drilling of holes in aerospace alloys, namely Inconel 718 and Ti-6Al-4V. The single-channel electrode produced comparatively better material removal rates and lower electrode wear ratio than multi-channel electrodes. Kuppan et al. [4] studied the influence of copper electrode on material removal rate and surface roughness. They optimized the process parameters using desirability function approach. To enhance the EDM performance during machining of Inconel 718, Kumar et al. [5,6] used the aluminium powder mixed dielectric. The powder concentration of 6 g/l has resulted in maximum material removal rate and minimum surface roughness value. Rajesha et al. [7] drilled hole of diameter 12 mm and 20 mm depth in Inconel 718 work material using hollow copper tool. It was concluded that there is a significant effect of pulse current and duty factor on material removal rate and surface roughness. The pulse current was more efficient on hole quality characteristics such as hole taper and hole dilation than pulse duration in mirohole drilling of Inconel 718 [8]. Further, Yadav and Yadava [9] observed that the electrode rotation has substantive effect on surface roughness and average circularity of the hole made by EDD process. Similar results were also reported by Gaur and Bharti [10] that tool electrode rotation resulted in improved MRR and surface finish in Inconel 718. Yadav and Yadava [11] proposed a new approach of hybrid methodology comprising the Taguchi methodology coupled with response surface methodology for modelling and response surface methodology coupled with principal component analysis-based grey relational analysis for multi-objective optimization of process parameters in EDD of Inconel 718. Kuppan et al. [12] drilled holes of 3 mm dia and 62 mm depth in Inconel 718 using copper electrode. They studied the hole quality based on surface roughness, over cut and hole profile. Recently, Bozdana and Ulutas [13] studied the effectiveness of multi-channel brass electrode during EDD of Inconel 718 on the basis of material removal and electrode wear. It is evident from the above literature review that for small hole EDD in general copper and brass electrodes have been mostly used by the researchers. Most of the published papers on EDD of Inconel 718 are based on single electrode material. Hence, an attempt has been made in this paper to compare the effectiveness of three different electrode materials viz., copper, copper-tungsten and graphite during EDD of Inconel 718.

2. Experimental details

The experiments were conducted on a commercial die sinking EDM machine fitted with a rotary head for rotating the electrode and has provision for injection flushing through the electrode. The pertinent process parameters selected for the study are peak current (I), pulse time-on (t_{on}), duty factor (η) (i.e. pulse on-time / cycle time) and electrode rotational speed (N). Other factors such as gap voltage (40 V), machine servo sensitivity and flushing pressure (0.2 MPa) were kept constant during the experimentation. Three different commercial tube electrodes viz., copper, copper-tungsten and graphite of outside diameter around 3 mm were used for drilling. The ranges of process parameters were selected by conducting pilot studies and literature [4].The variable process parameters and their ranges are shown in Table 1. The machining performance was investigated by analysing Material Removal Rate (MRR), Electrode Wear Ratio (EWR) and Surface Roughness (SR). The experiments were planned using Box-Wilson Central Composite Design (CCD) method. Through holes of 25 mm depth were drilled. Thirty one experiments were conducted with each electrode according to the CCD.

Table 1 Process parameters and their levels for copper, copper-tungsten and graphite electrodes

Sl. No.	Parameter	Units	Notation	Levels				
				-2	-1	0	1	2
1	Peak current	A	I	2	4	6	8	10
				4*	6*	8*	10*	12*
2	Pulse on-time	µs	t_{on}	20	40	60	80	100
3	Duty factor	%	η	45	50	55	60	65
4	Electrode rotational speed	rpm	N	0	100	200	300	400
				0*	75*	150*	225*	300*

* Current and electrode rotational speed levels for Cu-W electrode

3. Results and Discussion

3.1 Regression modelling

In this present work, a second order polynomial was selected for developing the regression model relating the output responses and input parameters as shown in Eq. 1.

$$y = b_0 + \sum_{i=1}^{k} b_i x_{iu} + \sum_{i=1}^{k} b_{ii} x_{iu}^2 + \sum_{i<j=2}^{k} b_{ij} x_{iu} x_{ju} \quad ...(1)$$

Where, y is the output response (MRR, EWR and SR); b_0, b_i, b_{ii}, b_{ij} the coefficients; x_{iu} the variables (I, t_{on}, η, N); u the experiment number; k the factor number; x_{iu}^2 the higher order terms of a variable x_i and x_{iu}, x_{ju} the interaction terms. The regression coefficients calculated are shown in Table 2. The subsequent sections present the trend lines plotted (Figs. 1 – 3) using the regression equations developed and the effect of input parameters on the output responses.

3.2 Material removal rate

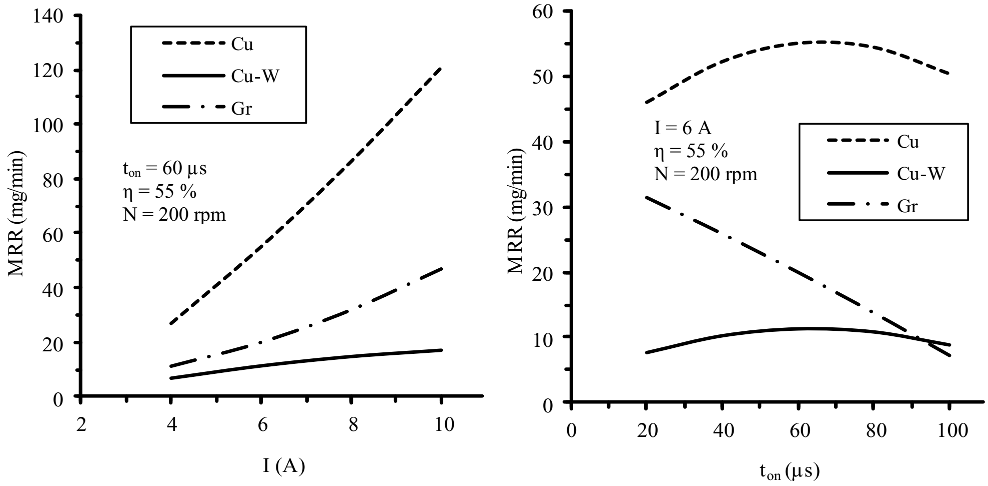
Fig. 1(a) shows the effect of current on MRR for copper, copper-tungsten and graphite tube electrodes. The trend indicates that MRR increases with the increase in current irrespective of electrodes and the relationship is almost directly proportional for all three electrodes. It is due to the fact that the spark discharge energy is increased to facilitate the action of melting and vaporization, and advancing the large impulsive force in the spark gap, thereby increasing the MRR. The results have shown that in addition to current, MRR is also dependent upon the electrode material. Analysis of results indicates that copper electrode produced the best MRR with increasing current followed by graphite and copper-tungsten electrodes. At fixed pulse on time of 60 µs, electrode speed of 200 rpm and duty factor of 55%, the percentage increase in MRR with copper is about 350% (26.877 to 120.784 mg/min), copper-tungsten gives a percentage increase of about

150% (6.762 to 17.029 mg/min) and graphite gives a percentage increase of about 320% (11.176 to 46.88 mg/min) when the average current is varied between 4 and 10 A. Further, it is to be noted that when machining using the copper electrode, machining speed is increasing approximately over seven times than the copper-tungsten electrode and over two and a half times than the graphite electrode at high current (10 A).

Table 2 Regression coefficients for MRR, EWR and SR

Coeff. Term	Copper			Copper-Tungsten			Graphite		
	MRR	EWR	SR	MRR	EWR	SR	MRR	EWR	SR
Const.	6.781	12.324	4.540	13.979	10.554	5.655	19.947	0.155	5.973
I	10.634	9.475	0.498	3.543	3.151	0.358	10.337	0.053	0.682
t_{on}	-4.299	-7.660	0.336	0.338	-0.633	0.307	-6.048	-0.064	0.283
η	0.230	-0.529	-0.032	-0.906	0.460	-0.044	-1.442	-0.018	0.037
N	0.956	-0.014	-0.045	1.604	2.023	-0.049	2.818	-0.021	0.022
$I \times I$	4.160	2.350	-0.071	-0.552	1.368	-0.040	1.565	0.020	-0.153
$t_{on} \times t_{on}$	1.182	2.899	-0.082	-0.763	-0.055	-0.172	-0.159	0.057	-0.312
$\eta \times \eta$	-0.130	0.054	-0.012	-0.339	0.072	-0.013	-0.436	-0.005	0.032
$N \times N$	-0.357	-0.304	0.048	-0.757	0.201	0.052	-1.438	0.022	-0.047
$I \times t_{on}$	-3.686	-3.599	0.101	0.552	-0.892	0.042	-2.238	0.000	0.203
$I \times \eta$	0.075	-0.961	-0.028	-0.986	1.215	-0.043	-1.616	-0.039	-0.170
$I \times N$	0.723	0.015	-0.069	-1.009	2.746	0.097	1.324	0.024	0.077
$t_{on} \times \eta$	-0.479	0.054	0.030	-0.868	0.839	-0.003	-0.622	0.021	0.156
$t_{on} \times N$	-0.007	0.606	-0.036	0.761	-0.793	-0.113	-0.215	-0.039	0.093
$\eta \times N$	0.166	0.064	0.021	-1.332	1.127	0.082	-1.003	0.011	0.243

Fig.1 (b) shows the effect of pulse on-time on MRR for copper, copper-tungsten and graphite tube electrodes. The pulse on-time is less significant on MRR for copper and copper-tungsten electrodes but significant for graphite electrode. The MRR gradually increases up to a pulse on-time around 60 µs and then decreases with the increase in pulse on-time for copper and copper-tungsten electrodes. It is interesting to note from the Fig. 1(b) that graphite shows a high sensitiveness to pulse on-time in comparison with metallic electrodes (copper and copper-tungsten). This abnormality of trend might be because of thermal, physical and micro structure of graphite material. The optimum pulse on-time for maximum MRR is around 60 µs for copper and copper-tungsten electrodes, and ~ 20 µs for graphite electrode within the range of investigation.



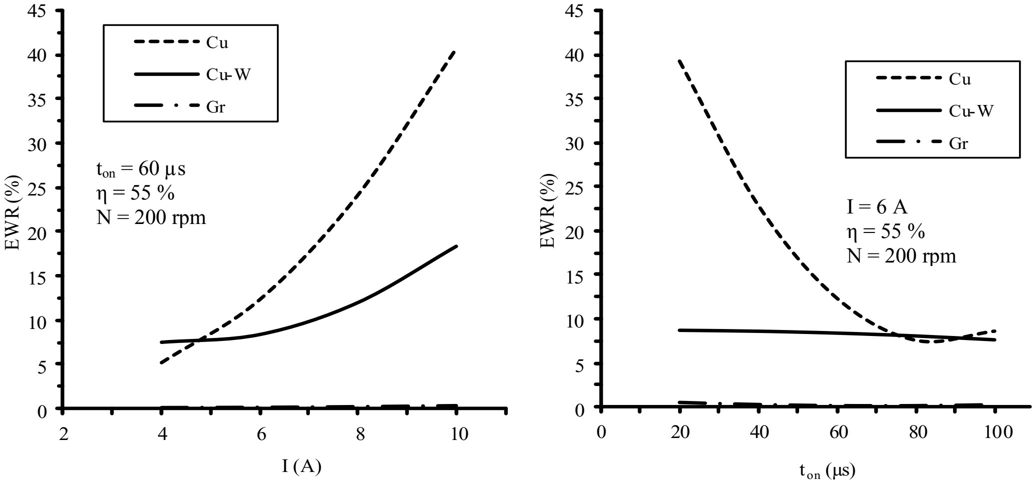
(a) **(b)**

Fig. 1 Effect of Cu, Cu-W and Gr electrodes on MRR

3.3 Electrode wear ratio

Fig. 2(a) shows the effect of current on EWR for copper, copper-tungsten and graphite electrodes. The EWR is high in copper electrode and followed by copper-tungsten and graphite electrodes. The graphite electrode shows minimum electrode wear (no wear range < 1 %) at all values of current. At fixed pulse on-time of 60 µs, electrode speed of 200 rpm and duty factor of 55%, EWR increases from 5.2% to 40.67% in copper, from 7.5% to 18.34% in copper-tungsten and from 0.122% to 0.341% in graphite electrodes as the current is varied between 4 and 10 A. The experiments have been carried out with positive polarity (i.e. tool is anode and work material is cathode), where the electrons strike the tool electrode surface liberating greater energy on the surface, and due to this action electrode erosion happens. The extent of electrode wear depends on the electrode materials and energy of the discharge. The higher the melting point of electrode material, lower the electrode erosion. The melting point of copper (1083°C) is less than that of graphite (3650°C) and copper-tungsten (3410°C), which resulted in more wear in copper electrode compared to other two electrodes.

Fig. 2(b) shows that as the pulse on-time increases EWR decreases for all the three electrodes. At current of 6 A, electrode speed of 200 rpm and duty factor of 55%, EWR for copper electrode decreases from 39.24% to 8.6%, for copper-tungsten electrode decreases from 8.69% to 7.62% and for graphite electrode decreases from 0.512% to 0.257% when the pulse on-time is varied between 20 and 100 µs. It is seen from the trend that for copper electrode, EWR decreases sharply as the pulse on-time increases (up to 80 µs) and then almost stable. In copper-tungsten and graphite electrodes, EWR is less sensitive to pulse on-time. One of the possible reason could be since copper is a good conductor of heat compared to other materials (thermal conductivity of copper is 392 W/m K, copper-tungsten is 220 W/m K and graphite is 95 W/m K) long pulse on-time resulted in decreased temperature at the electrode surface and less tool wear. The EWR being the ratio of tool wear to material removal, EWR decreases with pulse on-time. These trends agree with the theoretical work of Patel et al. [14]. For an anode electrode, the erosion rate increases as the current increases, but decreases as the pulse on-time increases.



(a) **(b)**

Fig. 2 Effect of Cu, Cu-W and Gr electrodes on EWR

3.4 Surface roughness

Fig. 3(a) shows the effect of peak current on SR for copper, copper-tungsten and graphite electrodes. The SR increases with increases in current irrespective of electrode materials and the increase in SR is proportional to the current value for all the three electrodes. The SR increases by 32% (3.97 to 5.25 μm), 30% (4.64 to 6.03 μm) and 31% (5.14 to 6.73 μm) with copper, copper-tungsten and graphite electrodes respectively at fixed pulse on time of 60 μs, electrode speed of 200 rpm and duty factor of 55% when the current is varied from 4 to 10 A. The analysis of results indicates that, copper exhibits the best performance with regard to SR while graphite shows the poorest. The copper-tungsten produces SR in between copper and graphite electrodes. One of the reasons for high SR with graphite electrode may be due to porous and coarse grain structure of graphite electrode. The open structure of its grain imprints into the workpiece, after all EDM is a copying process. The copper electrode has produced good surface finish in Inconel 718 work material. The reason for obtaining low SR with copper electrode is due to the better electrical and thermal properties of copper compared to that of copper-tungsten and graphite. If the conductivity of the electrode is better, then it facilitates the uniform and effective pulse discharges reducing ineffective pulses like short circuits and arcing. Therefore, the frequency of pulse increases, which is an important criterion for fine surface finish as high frequency and low amperage provide better surface finish. Similar observations were also made by other investigators [15, 16] for copper electrode while machining different work materials.

Fig. 3(b) also depicts the effect of pulse on-time on SR for copper, copper-tungsten and graphite electrodes. As the pulse on-time increases, SR increases for copper electrode and the increase in SR is less sensitive at extended pulse on-time (>60 μs). Whilst for copper-tungsten and graphite electrodes SR gradually increases with the increase in pulse on-time upto 60 μs and then it starts decreasing. At fixed average current of 6 A, electrode speed of 200 rpm and duty factor of 55%, SR increases by about 40% (3.54 to 4.88 μm) for copper electrode as the pulse on-time varies from 20 to 100 μs. For copper-tungsten and graphite electrode, SR increases by about 26% (4.11 to 5.18 μm) and by about 44% (4.16 to 5.97 μm), respectively as pulse on-time varied from 20 to 60 μs and beyond which it starts decreasing. At high pulse on- time, the spark intensity is decreasing in the discharge spots because of the expansion of the plasma channel. Hence, it is understood that at extended pulse on-time duration (> 60 μs), the surface roughness is being decreased.

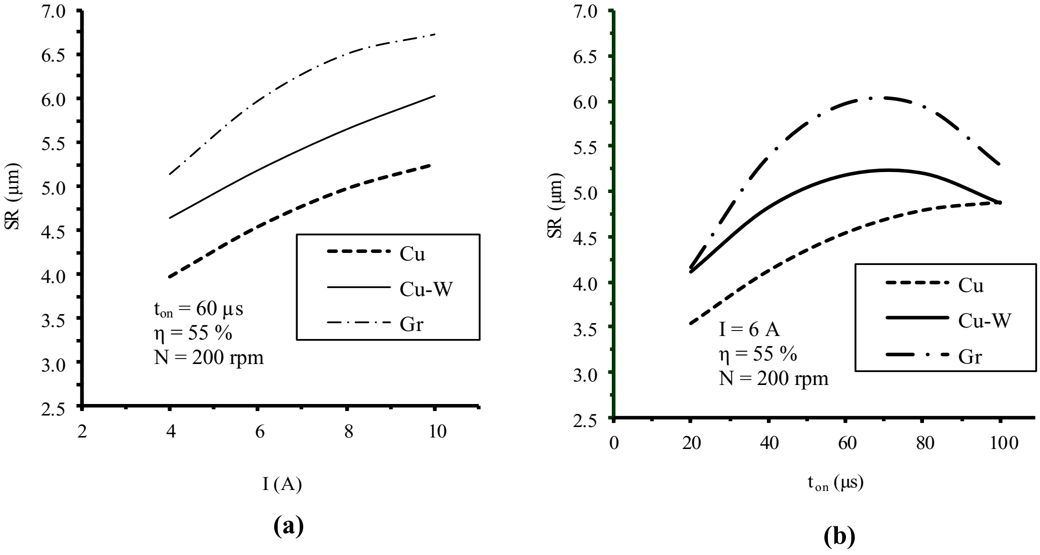


Fig. 3 Effect of Cu, Cu-W and Gr electrodes on SR

4. Conclusions

The aim of the present investigation was to study the influence of different tool electrode materials such as copper, copper-tungsten and graphite in electric discharge drilling of small diameter deep holes in Inconel 718 superalloy. The main requirements for of any tool electrode material in small diameter electric discharge drilling are it must produce high MRR combined with low surface roughness and low electrode wear ratio. The experimental results revealed that copper electrode produced high material removal rate and low surface roughness. The graphite electrode resulted in low electrode wear ratio (<1%), moderate material removal rate and high surface roughness. Whereas, the copper-tungsten electrode produced low material removal rate with moderate surface roughness and electrode wear ratio. From the point of view of low EWR, graphite electrode would certainly be the best tool electrode. But, due to brittleness and difficulty in fabricating large aspect ratio small diameter tube electrode, graphite is not generally preferred for small diameter deep hole drilling. From the economic point of view, copper tube electrode is more attractive. Among the three electrodes used in the present study, copper electrode is the best choice for electric discharge deep hole drilling of Inconel 718 which gives high material removal rate and low surface roughness.

References

[1] Hassan Abdel-Gawad El-Hofy, 2015, Advanced Machining Processes: Nontraditional and Hybrid Machining Processes, McGraw-Hill Education, , New York.

[2] Wang, K., Gelgele, H.L., Wang, Y., Yuan, Q. and Fang, M. (2003) 'A hybrid intelligent method for modelling the EDM process', International Journal of Manufacturing and Management, Vol. 43, No. 10, pp.995–999.

[3] Yilmaz, O. and Okka, M.A. (2010) 'Effect of single and multi-channel electrodes application on EDM fast hole drilling performance', International Journal of Advanced Manufacturing Technology, Vol. 51, Nos. 1–4, pp.185–194.

[4] Kuppan, P., Rajadurai, A. and Narayanan, S. (2008) 'Influence of EDM process parameters in deep hole drilling of Inconel 718', International Journal of Manufacturing and Technology, Vol. 38, Nos. 1–2, pp.74–84.

[5] Kumar, A., Maheshwari, S., Sharma, C. and Beri, N. (2011) 'Analysis of machining characteristics in additive mixed electric discharge machining of nickel-based super alloy Inconel 718', Materials and Manufacturing Processes, Vol. 26, No. 8, pp.1011–1018.

[6] Kumar, A., Maheshwari, S., Sharma, C. and Beri, N. (2012) 'Machining efficiency evaluation of cryogenically treated copper electrode in additive mixed EDM', Materials and Manufacturing Processes, Vol. 27, No. 10, pp.1051–1058.

[7] Rajesha, S., Sharma, A.K. and Kumar, P. (2012) 'On electro discharge machining of Inconel 718 with hollow tool', Journal of Materials Engineering and Performance, Vol. 21, No. 6, pp.882–891.

[8] Ay, M., Çaydaş, U. and Hasçalık, A. (2013), 'Optimization of micro-EDM drilling of inconel 718 superalloy', Int J Adv Manuf Technol, Vol. 66, pp. 1015-1023

[9] Yadav US, Yadava V (2014), 'Parametric study on Electrical Discharge Drilling of Aerospace Nickel Alloy', International Journal of Materials and Manufacturing Processes, Vol. 29, 260-266.

[10] Sanjay Gaur, PK Bharti, 2015, 'Experimental Study with Rotating Tool Electrode of EDM for NiAlloy', International Journal of Modern Engineering Research, Vol. 5 (1), pp. 15-22.

[11] Yadav US, Yadava V (2015), 'Experimental modeling and multiobjective optimization of electrical discharge drilling of aerospace superalloy material', Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 229 (10), pp. 1764-1780

[12] Kuppan, P., Narayanan, S., Rajadurai, A. and Adithan, M. (2015) 'Effect of EDM parameters on hole quality characteristics in deep hole drilling of Inconel 718 superalloy', Int. J.Manufacturing Research, Vol. 10, No. 1, pp.45–63

[13] Ali Tolga Bozdana and Tugba Ulutas (2016), 'The Effectiveness of Multichannel Electrodes on Drilling Blind Holes on Inconel 718 by EDM Process', International Journal of Materials and Manufacturing Processes, Vol. 31(4), pp. 504-513

[14] Patel, M.R. and Barrufet, M.A., Eubank, P.T and DiBitonto, D.D. (1989), 'Theoretical models of the electrical discharge machining process-II A simple anode erosion model', J. Appl. Phys., Vol. 66(9), pp. 4104-4111.

[15] Lonardo, P.M. and Bruzzone, A.A. (1999) 'Effect of flushing and electrode material on die sinking EDM', CIRP Annals, Vol. 48(1), pp. 123-126.

[16] Singh, S., Maheshwari, S. and Pandey, P.C. (2004). 'Some investigations into the electric discharge machining of hardened tool steel using different electrode materials', J. Mater. Process. Technol., Vol.149(1-3), pp. 272-277.