

Performance Evaluation of Powder Metallurgy Electrode in Electrical Discharge Machining of AISI D2 Steel Using Taguchi Method

Naveen Beri, S. Maheshwari, C. Sharma, Anil Kumar

Abstract—In this paper an attempt has been made to correlate the usefulness of electrodes made through powder metallurgy (PM) in comparison with conventional copper electrode during electric discharge machining. Experimental results are presented on electric discharge machining of AISI D2 steel in kerosene with copper tungsten (30% Cu and 70% W) tool electrode made through powder metallurgy (PM) technique and Cu electrode. An L18 (21 37) orthogonal array of Taguchi methodology was used to identify the effect of process input factors (viz. current, duty cycle and flushing pressure) on the output factors {viz. material removal rate (MRR) and surface roughness (SR)}. It was found that CuW electrode (made through PM) gives high surface finish where as the Cu electrode is better for higher material removal rate.

Keywords—Electrical discharge machining (EDM), Powder Metallurgy (PM), Taguchi method, Material Removal Rate (MRR), Surface Roughness (SR).

I. INTRODUCTION

ELECTRICAL DISCHARGE MACHINING is a thermo-electrical material removal process, in which tool electrode shape is reproduced mirror wise into a work material, with the shape of the electrode defining the area in which the spark erosion will occur [1]. It has been widely used to produce dies, molds, aerospace, automotive industry and surgical components [2]. It is also useful for machining brittle materials, as there is virtually no contact between the tool and work-piece.

In EDM, the material is removed primarily through the conversion of electrical energy into thermal energy through a series of successive sparks between the electrode and the work piece in a dielectric fluid. The thermal energy is consumed in generating high temperature plasma, eroding the work piece material. Moreover there is no direct contact between the electrode and the work piece which eliminates mechanical stresses chatter and vibration problems during machining.

Naveen Beri is with Department of Mechanical Engineering, Beant College of Engineering & Technology, Gurdaspur, Punjab, India. (e-mail: nav_beri74@yahoo.co.in).

S. Maheshwari, is with Division of Manufacturing Process & Automation Engineering, Netaji Subash Institute of Technology, Dwarka, New Delhi, India. (e-mail: ssaacchhiinn@gmail.com).

C. Sharma is with Department of Mechanical and Automation Engineering, IGIT, Kashmiri Gate, Delhi, India. (e-mail: chitrabisht@rediffmail.com).

Anil Kumar is with Department of Mechanical Engineering, Beant College of Engineering & Technology, Gurdaspur, Punjab, India. (phone: +91-9417286270 ; fax: +911874-221463; e-mail: ak_101968@yahoo.com).

The recent developments in the field of EDM have progressed due to the growing application of EDM process and the challenges being faced by the modern manufacturing industries, from the development of new materials that are hard and difficult-to-machine such as tool steels, composites, ceramics, super alloys, hastalloy, nitralloy, waspalloy, nemonics, carbides, stainless steels, heat resistant steel, etc.

Typically, the major cost and time components in die and mould machining by EDM are in the electrode fabrication, which can account for over 50% of the total machining cost [3]. Typical materials, used as EDM electrodes include copper, brass, chromium, tungsten, steel, copper-tungsten and copper chromium alloys [4,5,6]. Conventional methods of fabricating the electrodes include stamping, coining, grinding, extrusion, drawing, and more commonly, turning, milling, incurring long processing time and material wastage especially if a complex geometry or profile is required [4].

EDM research has concentrated on achieving faster and more efficient metal removal rate coupled with a reduction in tool wear and improved surface characteristics [7, 8, 9]. The majority of work has been done using mechanically formed tool electrodes and the present EDM user is compelled to search for alternative tooling such as powder metallurgy (PM) method of electrode fabrication which is more economic and faster to manufacture. A complex electrode made by conventional method can cost around 100 times more than a simple square electrode. However, in the PM route a large number of tool electrodes can be made from a single die and punch assembly, resulting in an overall reduction of EDM tooling cost. Therefore, PM turns out to be a viable alternative to produce tool electrode in which the desirable properties of different materials can be combined. Moreover, the thermal, electrical, mechanical and micro structural properties of PM tool electrodes can be effectively controlled by the process variables such as compacting pressure and sintering temperature. These will affect density and pore shape. An example is an alloy of CuW made through PM where tungsten particles are uniformly embedded in highly conductive copper matrix. The electrodes made by using powder metallurgy technology from special powders have been used to modify EDM surfaces in recent years, to improve wear and corrosion resistance.

Gangadhar et al. [10] reported surface deposition by EDM in a liquid dielectric using PM compact tool electrode. Deposition of tungsten carbide on flank and rake of a HSS tool using PM electrode containing 40%WC and 60% Fe (zinc stearate as lubricant) with reverse polarity and kerosene as dielectric resulted in low variation in cutting forces. Soni and Chakraverti [11] found that appreciable amount of elements

has migrated from the tool electrode to work piece and vice versa and got alloyed in the resolidified layer causing a change in chemical composition and significant increase in surface hardness of the work piece during electro-discharge machining of high carbon high chromium die steel (hardened) with rotating copper-tungsten tool electrode. EDMing of hardened steel (BS 970817M40, 53Rc) work material of Cu electrode made through PM and paraffin as dielectric has been reported by Samual et al. [12]. Wang, et al. [13] described a new method of surface modification by EDM. By using an ordinary EDM machine tool and kerosene fluid, a hard ceramic layer can be created on the work piece surface with a Ti or other compressed powder electrode in a certain condition. It was observed that a compact TiC ceramic layer can be created on the surface of the metal work piece. Blending of copper powders containing resin with chromium powders to form tool electrode has been investigated by Tsai et al. [14]. Lee et al. [15] investigated the small area EDM process using a copper-tungsten electrode on AISI 1045 carbon steel and has reported that the values of the MRR, SR increase for higher values of pulse current. Ferreira [16] observed that copper-tungsten electrodes with negative polarity are suitable for the planetary EDM surface micro-finishing of die steel (AISI H13) with good geometry accuracy and sharp details. Chen et al. [17] has investigated how machining characteristics and surface modifications affect low-carbon steel (S15C) during electrical discharge machining (EDM) processes with semi-sintered electrodes. It was found that the composition of the semi-sintered electrodes was transferred onto the machined surface efficiently and effectively during the EDM process and that the process is feasible and can easily form a modified layer on the machined surface.

From the above reviewed literature it is observed that PM tool electrodes have a significant role in metal removal process in addition to their contribution in surface treatment/modification applications and a need is felt to correlate the usefulness of CuW electrode made through powder metallurgy (PM) with a view to optimize the process parameters [10,18,19,20].

The present experimental work is focused on the electrical discharge machining of AISI D2 steel with CuW (30% Cu and 70% W) electrode made through PM technique in comparison with convention Cu electrode and an attempt has been made to obtain optimal setting of the process input parameters for optimum MRR and SR with kerosene as dielectric fluid. Taguchi methodology has been applied to plan and analyze the experiments.

II. EXPERIMENTAL WORK

A. Experimental Planning (Taguchi Method)

Taguchi method uses special design of orthogonal array to study the entire parameters space with only a small number of experiments. In selecting an appropriate OA, the pre-requisites are (i) selection of process parameters and interactions to be evaluated (ii) selection of number of levels for the selected parameters, and (iii) evaluation of total degree of

freedom based upon number of parameters and their levels. The non-linear behavior of the process parameters, if exists, can only be revealed if more than two levels of the parameters are investigated. Therefore, parameter A was analyzed at two levels and parameter B, C & D were analyzed at three levels. Experimental parameters and their levels selected for the study are tabulated in Table 1 and all other parameters are kept constant.

TABLE I
 MACHINING PARAMETERS LEVELS

Factor symbol	Parameter	Level 1	Level 2	Level 3
A	Electrode Material	Copper (Cu)	Copper Tungsten (CuW)	---
B	Current I (amp)	4.5	7.5	10.5
C	Duty Cycle	0.5	0.66	0.78
D	Flushing Pressure F_p (Kg/cm ²)	0.3	0.5	0.7

It was decided to study the two factor interaction effects and the selected interactions were: (i) between current and duty cycle (B×C) and (ii) between current and flushing pressure (B×D) and other interactions are neglected. There are 7 degree of freedom owing to one two level parameter and three three level parameters and the degree of freedom of interactions selected is 8. The total degree of freedom is 7+8 = 15. A mixed orthogonal array L18 (21 37) was used for experimentation as it has degree of freedom 17 which is more than degree of freedom of selected machining parameters and interactions (7+8=15).

To obtain optimal machining performance, the maximum MRR and the minimum SR are desired. Therefore, the lower-the-better SR and the higher-the-better MRR criteria was selected.

The loss function L_{ij} of the lower-the-better performance characteristic can be expressed as

$$L_{if} = \frac{1}{n} \sum_{k=1}^n \frac{1}{y_{ijk}^2} \quad (1)$$

where L_{ij} is the loss function of the i th performance characteristic in the j th experiment, n the number of tests, and y_{ijk} is the experimental value of the i th performance characteristic in the j th experiment at the k th test.

The loss function of the higher-the-better performance characteristic can be expressed as

$$L_{if} = \frac{1}{n} \sum_{k=1}^n y_{ijk}^2 \quad (2)$$

The loss function is further transformed into an S/N ratio. In the Taguchi method, the S/N ratio is used to determine the deviation of the performance characteristic from the desired value [21]. The S/N ratio Z_{ij} for the i th performance characteristic in the j th experiment can be expressed as

$$n_{ij} = -10 \log(L_{ij}) \quad (3)$$

B. Experimental Procedures and Parameters

The experiments were carried out on a standard EDM machine; model SPARKMAN (S-10) of Sparkonix with straight polarity. AISI D2 Steel (specimens 85mm X 25mm X 3mm) hardened to 55-58 HRC was used as work piece material with commercial grade kerosene as the dielectric fluid. Cylindrical Cu electrodes (ϕ 8mm) and CuW electrodes made through powder metallurgy (Cu30%, W70%, ϕ 8mm) were used for the experimentation.

Work piece was weighed on digital balance (accuracy 1 mg) to get the initial weight before machining. Then erosion was switched on for a depth of cut of 1mm and time taken to complete the operation was noted and the work piece was weighed again. The surface roughness (Ra value in microns) was measured on Surfcoeder (model SE 1200, make Kosaka Laboratory Ltd., Japan). Two sets of 18 experiments (as depicted in coded form in Table 2) were performed as per L18 ($2^1 \times 3^7$) Taguchi design and average value of each output parameter were statistically analyzed using Minitab 14.1 software.

TABLE II
EXPERIMENTAL LAYOUT USING MIXED ORTHOGONAL ARRAY L18 ($2^1 \times 3^7$)

Exp. No.	Electrode material (A)	Current (I) (amp) (B)	Duty Cycle (DC) (C)	Flushing Pr. (P) (Kg/cm ²) (D)
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	1
5	1	2	2	2
6	1	2	3	3
7	1	3	1	2
8	1	3	2	3
9	1	3	3	1
10	2	1	1	3
11	2	1	2	1
12	2	1	3	2
13	2	2	1	2
14	2	2	2	3
15	2	2	3	1
16	2	3	1	3
17	2	3	2	1
18	2	3	3	2

III. RESULTS AND DISCUSSIONS

The mean effects plots of the S/N ratios for the output measures are obtained using Minitab 14.1 software. Plots with the steeper slope along with longer lines shows that the factor has significant impact on the output parameter.

A. Analysis of Material Removal Rate (MRR)

The average values of S/N ratios for MRR at different levels are plotted in Fig. 1 keeping the objective as "larger is better". In order to study the significance of the parameters in effecting the quality characteristic of interest i.e. MRR ANOVA was performed. The S/N ANOVA for MRR is given in Table 3. The result of ANOVA indicates that electrode

material, current, duty cycle and flushing pressure effect the multiple performance characteristics.

TABLE III
ANOVA FOR MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	1	189.420	189.420	189.420	57.39	0.017
B	2	479.116	479.116	239.558	72.58	0.014
C	2	12.549	13.440	6.720	2.04	0.329
D	2	8.230	5.865	2.932	0.89	0.530
BXC	4	1.231	2.075	0.519	0.16	0.943
BXD	4	2.663	2.663	0.666	0.20	0.917
Residual						
Error	2	6.601	6.601	3.301		
Total	17	699.810				

It is clear from fig. 1 that MRR is maximum at the 1st level of parameter A, 3rd level of parameter B, 2nd level of parameter C and 3rd level of parameter D. The S/N ratio analysis suggests the same levels of the parameters (A₁, B₃, C₂ and D₃) as the best levels for maximum MRR.

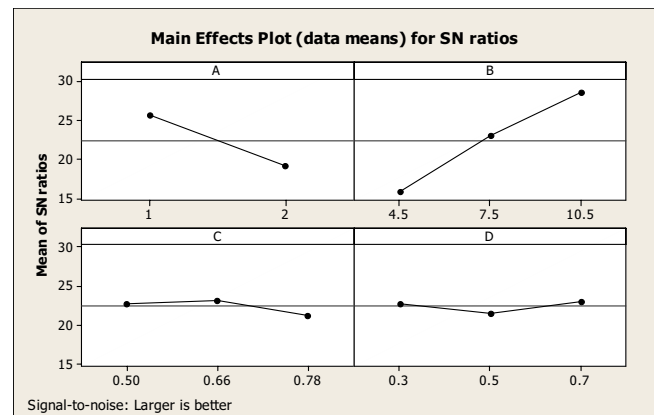


Fig. 1 Mean effect plot for S/N ratios for material removal rate (MRR)

The interaction graph (Fig. 3) also reveals that B₃, C₂ and D₃ is the best treatment combination to give maximum MRR. These graphs show significant influence of current on the output parameters. MRR increases with the increase in current for both the electrodes but it is less with CuW electrode as compared with Cu electrode this can be attributed to the deposition of material from CuW electrode on the work piece and its lower conductivity.

B. Analysis of Surface Roughness (SR)

The average values of S/N ratios for SR at different levels are plotted in Fig. 3 keeping the objective as "smaller is better". In order to study the significance of the parameters in affecting the quality characteristic of interest i.e. SR ANOVA was performed. The S/N ANOVA for SR is given in Table 3. The result of ANOVA indicates that electrode material, current, duty cycle and flushing pressure effect the multiple performance characteristics.



Fig. 2 Interaction plot for S/N ratios for material removal rate (MRR)

TABLE IV
 ANOVA FOR SR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	1	15.213	15.213	15.213	4.98	0.155
B	2	349.624	349.624	174.812	57.28	0.017
C	2	6.037	4.062	2.031	0.67	0.600
D	2	0.606	0.015	0.008	0.00	0.998
BXC	4	3.058	2.361	0.590	0.19	0.922
BXD	4	0.143	0.143	0.036	0.01	0.999
Residual						
Error	2	6.104	6.104	3.052		
Total	17	380.784				

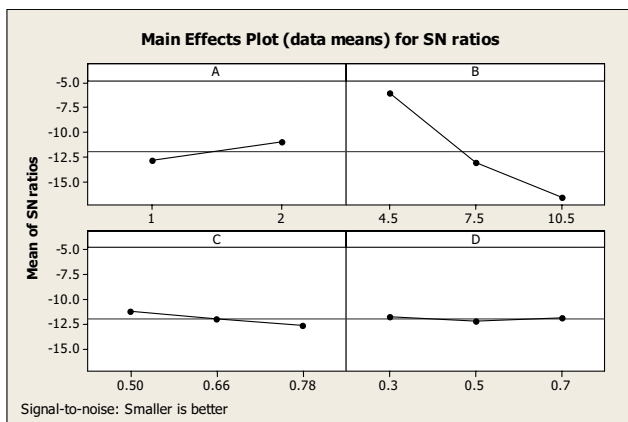


Fig. 3 Mean effect plot for S/N ratios for surface roughness (SR)

It is clear that SR is minimum at the 2nd level of parameter A, 1st level of parameter B, 1st level of parameter C and 1st level of parameter D. The S/N ratio analysis suggests the same levels of the parameters (A₂, B₁, C₁ and D₁) as the best levels for maximum SR. The interaction graph (Fig. 4) also reveals that B₁, C₁ and D₁ are the best treatment combination to give maximum MRR. From the graph it is clear that with the increase in current surface roughness increases and CuW electrode made through PM is better as compared to conventional Cu electrode this can be attributed to the of deposition of electrode material on the work piece causing a reduction in surface cracks resulting in decrease of surface roughness.

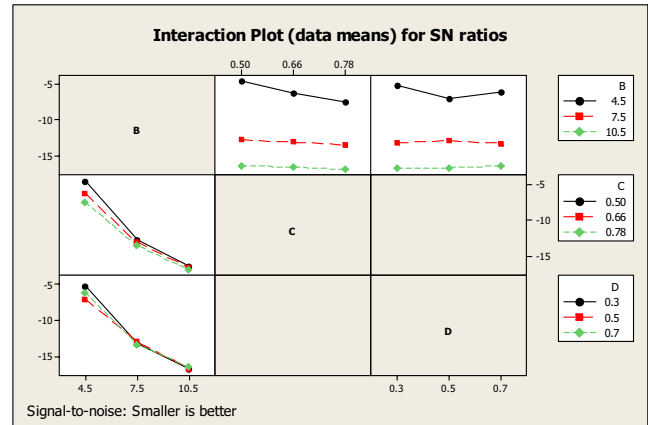


Fig. 4 Interaction plot for S/N ratios for surface roughness (SR)

Confirmation experiment was performed at A₁, B₃, C₂ and D₃ levels of the parameters for maximum MRR as suggested by the mean effect plot of MRR and MRR obtained is 43.0211 mg/min. Another confirmation experiment was performed at A₂, B₁, C₁ and D₁ levels of the parameters for maximum SR as suggested by the mean effect plot of SR and the SR obtained is 1.38 microns.

IV. CONCLUSIONS

The Taguchi approach employed enabled the identification of significant factors and their associated levels on specific output measures. Selection of appropriate operating values from these data enabled preferred work piece characteristics to be achieved. During EDMing of AISID2 steel it is found that electrode material, current and duty cycle has significant effect on both the performance parameters. Best parameter selection with in the experiment range for maximum MRR is with copper electrode at 10.5 A current, 0.66 duty cycle and 0.7 Kg/cm² flushing pressure i.e. A₁B₃C₂D₃ and for minimum surface roughness is with copper tungsten electrode at 4.5 A current, 0.50 duty cycle and 0.3 Kg/cm² flushing pressure i.e. A₂B₁C₁D₁. From above it is obtained that Cu electrode is better for higher MRR and CuW electrode gives minimum surface roughness. So if the requirement is to have high MRR then it is recommended to use Cu electrode and if the requirement is to have better surface finish only on the machined surface of AISI D2 steel then it is recommended to use CuW electrode made through PM.

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