

Study on effect of tool electrodes on surface finish during electrical discharge machining of Nitinol

Anshuman Kumar Sahu, Suman Chatterjee, Praveen Kumar Nayak,
Siba Sankar Mahapatra

Department of Mechanical Engineering,
National Institute of Technology Rourkela, Odisha, India

Corresponding author Email : anshuman.sahu123@gmail.com

Abstract: Electrical discharge machining (EDM) is a non-traditional machining process which is widely used in machining of difficult-to-machine materials. EDM process can produce complex and intrinsic shaped component made of difficult-to-machine materials, largely applied in aerospace, biomedical, die and mold making industries. To meet the required applications, the EDMed components need to possess high accuracy and excellent surface finish. In this work, EDM process is performed using Nitinol as work piece material and AlSiMg prepared by selective laser sintering (SLS) as tool electrode along with conventional copper and graphite electrodes. The SLS is a rapid prototyping (RP) method to produce complex metallic parts by additive manufacturing (AM) process. Experiments have been carried out varying different process parameters like open circuit voltage (V), discharge current (Ip), duty cycle (τ), pulse-on-time (Ton) and tool material. The surface roughness parameter like average roughness (Ra), maximum height of the profile (Rt) and average height of the profile (Rz) are measured using surface roughness measuring instrument (Talysurf). To reduce the number of experiments, design of experiment (DOE) approach like Taguchi's L_{27} orthogonal array has been chosen. The surface properties of the EDM specimen are optimized by desirability function approach and the best parametric setting is reported for the EDM process. Type of tool happens to be the most significant parameter followed by interaction of tool type and duty cycle, duty cycle, discharge current and voltage. Better surface finish of EDMed specimen can be obtained with low value of voltage (V), discharge current (Ip), duty cycle (τ) and pulse on time (Ton) along with the use of AlSiMg RP electrode.

1. Introduction

Electro-discharge machining (EDM) is a mostly used non-traditional machining process due to its capability to produce complex, intrinsic cavity with excellent surface finish for applications in aerospace, biomedical, automobile, tool and die industries. In the EDM process, the work piece and the tool electrodes are immersed inside a dielectric medium. When the voltage is applied to the system, spark is generated in the electrode gap with generation of very high temperature (around 10000°C). High temperature causes to melt and vaporize tiny amount of material from the work piece surface and leads to the removal of material from the work piece surface. EDM process is used for machining of hard-to-machine materials with reasonably accurate dimensions and surface finish to meet the requirement of the industries [1]. During EDM process, maximum time is devoted to produce the tool electrode which needs the use of conventional or non-conventional machining processes. Development of the tool electrode not only consumes the overall time required for the EDM process but also increases the cost of production of the final product. In order to reduce the manufacturing time of electrodes, rapid prototyping (RP) process like selective laser sintering (SLS) process can be used. By using the RP process, the preparation time for tool electrodes is reduced by 50%, which reduced the overall production cost of final product [2, 3].

Different type of EDM electrodes like bronze-nickel with copper phosphite by SLS, epoxy with silver paint and copper coating by thin coated stereolithography (SL) model, steel and phosphate taking polyester as binder by SLS were prepared by RP process and used in EDM [2-4]. Complex steel mold was prepared by EDM process by taking tool electrode of graphite prepared by RP process with the use of abrading tool of corundum and SiC [5]. Similarly, mold from steel work piece was prepared by EDM process by taking copper electrode prepared by electroforming process and graphite electrode prepared by abrading process [6]. From these works, it is found that rapid tooling (RT) technology is a rapid and effective technique to manufacture mold and RT has high prospective for reduction in time and cost.



In this work, EDM performance of AlSiMg electrode prepared by SLS process along with conventional copper and graphite electrodes have been studied during the machining of Nitinol. Here performance of the AlSiMg composite electrode is investigated by varying different EDM process parameters to enhance the surface properties of the machined specimen and compare to the performance of conventional copper and graphite tool electrodes. Nitinol is a nickel-titanium alloy used in aerospace, automobile, biomedical and chemical industries due to its high strength and corrosion resistance in a wide range of temperature variations. To meet the required applications in the field of chemical, aerospace, biomedical, die and mold making industries, the EDM specimen must be prepared with high precision and excellent surface finish. To examine the surface roughness characteristics (average roughness (Ra), average height of the profile (Rz) and maximum height of the profile (Rt)) of the machined surface during electrical discharge machining, different EDM input parameters like voltage (V), discharge current (Ip), duty cycle (τ) and pulse-on-time (Ton) have been varied along with different types of tool electrodes i.e. AlSiMg RP electrode, copper and graphite electrodes.

2. Materials and methods

In this work, AlSiMg RP electrode prepared by SLS process, copper and graphite are used as tool electrode for the EDM of Nitinol as work piece material and commercial EDM 30 oil as dielectric fluid. The chemical composition of Nitinol in weight percentage of the elemental component is given in Table 1.

Table 1. Chemical composition of Nitinol

Composition	Ni	Cr	Cu	Fe	Nb	Co	O	C	Ti
Weight percentage	55.64	<0.01	<0.01	<0.012	<0.01	<0.01	<0.05	<0.02	Balance

Table 2. Machining parameters with their levels

Parameters	Unit	Level-1	Level-2	Level-3
A-Voltage (V)	V	20	25	30
B-Discharge current (Ip)	A	20	25	30
C-Duty cycle (τ)	%	67	75	83
D- Pulse-on-time (Ton)	μs	100	200	300
E-Tool type	-	AlSiMg RP	Graphite	Copper

To study the effect of different types of tools like AlSiMg RP electrode, copper and graphite electrodes on the surface roughness of the machined surfaces, the EDM process parameters like voltage (V), discharge current (Ip), duty cycle (τ) and pulse on time (Ton) are varied during the EDM process. The values of the input parameters with different levels are listed in Table 2. To reduce the number of experiments, design of experiment (DOE) methodology like Taguchi’s L₂₇ orthogonal array is considered. The EDM process of work piece material Nitinol by taking different tool electrodes has been performed in a EDM (model: ELECTRA EMS 5535). The surface quality parameters like average roughness (Ra), average height of the profile (Rz) and maximum height of the profile (Rt) are measured by the use of surface roughness measurement machine (Taylor-Hobson-PNEUNO-Suetronic 3+) [7,8]. Here, the surface roughness parameters are measured three times and the average value for each EDM machined specimens is considered for further study. The surface roughness values are optimized by desirability approach (DA) and best optimal setting is obtained to get better surface finish of the machined specimens.

Average roughness (Ra) is the arithmetic mean of the absolute values of the heights of the contour along the estimated length. The average roughness (Ra) is estimated by the formula as given in Eqn. (1).

$$\text{Average roughness, } Ra = \frac{1}{L} \int y(x) dx = \frac{\sum_{i=1}^{i=n} y_i}{n} \tag{1}$$

Maximum height of the profile (Rt) is the perpendicular distance amongst the uppermost and bottommost points of the contour inside the estimated length. The maximum height of the profile (Rt) is calculated as in Eqn. (2).

$$\text{Maximum height of the profile, } Rt = \text{Max}(y_i) \tag{2}$$

Average height of the profile (Rz) is the mean of the consecutive values of maximum height of the profile (Rt) calculated over the estimated length as mentioned in Eqn. (3).

$$\text{Average height of the profile, } Rz = \frac{\sum_{i=1}^n R_{ti}}{n} \tag{3}$$

where L = sampler length, y = profile curve, x = profile direction, y_i = height of the profile. The surface roughness values are measured within L=0.8mm having cut off length Lc=0.4mm and N=2.

2.1. Desirability function approach

The desirability function approach is a optimization technique used to solve multi objective optimization problems. The elementary conception of desirability is to transform multi objective optimization problem into single objective. Here, each response variable y_i is converted into individual desirability value d_i, which value ranges between 0 to 1. If the characteristic of the output response is unacceptable, then desirability value is 0 and for optimal acceptable characteristic the desirability value is 1. After that composite or overall desirability is then calculated from the individual desirability. The highest value of the overall desirability indicates the optimum parametric setting [9-11]. The following steps are followed to evaluate the individual desirability index (d_i) and overall desirability index (d_o).

1. Calculation the individual desirability index (d_i).

(i) Nominal is the best.

$$d_i = \begin{cases} \left(\frac{y_i - y_{min}}{T - y_{min}}\right)^s, & y_{min} \leq y_j \leq T, s \geq 0 \\ \left(\frac{y_i - y_{max}}{T - y_{max}}\right)^s, & T \leq y_j \leq y_{max}, s \geq 0 \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

(ii) Larger is the better.

$$d_i = \begin{cases} 0, & y_i \leq y_{min} \\ \left(\frac{y_i - y_{min}}{y_{max} - y_{min}}\right)^r, & y_{min} \leq y_j \leq y_{max}, r \geq 0 \\ 1, & y_j \geq y_{min} \end{cases} \tag{5}$$

(iii) Smaller is the better.

$$d_i = \begin{cases} 1, & y_i \leq y_{min} \\ \left(\frac{y_i - y_{max}}{y_{min} - y_{max}}\right)^r, & y_{min} \leq y_j \leq y_{max}, r \geq 0 \\ 0, & y_j \geq y_{min} \end{cases} \tag{6}$$

where y_j= observed value from the experiment.

y_{max}= maximum observed value

y_{min}= minimum observed value

T = Target value

2. Calculate the composite or overall desirability.

$$d_o = (d_1^{w_1} * d_2^{w_2} * \dots * d_i^{w_i})^{1/w} \tag{7}$$

where w₁ + w₂ + ... w_i = w

3. Result and Discussion

The experiment of EDM is performed for the Nitinol work piece and the surface roughness parameters were measured as described in section 2. The surface roughness parameters like average roughness (Ra), average height of the profile (Rz) and maximum height of the profile (Rt) are measured for three numbers of times and the average value is consider for further analysis.

3.1 Effect of parameters on Ra

The main effect plot for average roughness (Ra) is presented in Figure 1. From the figure it is found that with increase in EDM parameters like voltage (V), discharge current (Ip), duty cycle (τ) and pulse on time (Ton), the average surface roughness (Ra) of the machined surface increased. This is due to the regeneration of more energy during sparking, which leads to more crater depth with increased average surface roughness (Ra). The surface of specimen machined with RP electrode is better with respect to average surface roughness (Ra) followed by surface machined with copper and graphite electrodes.

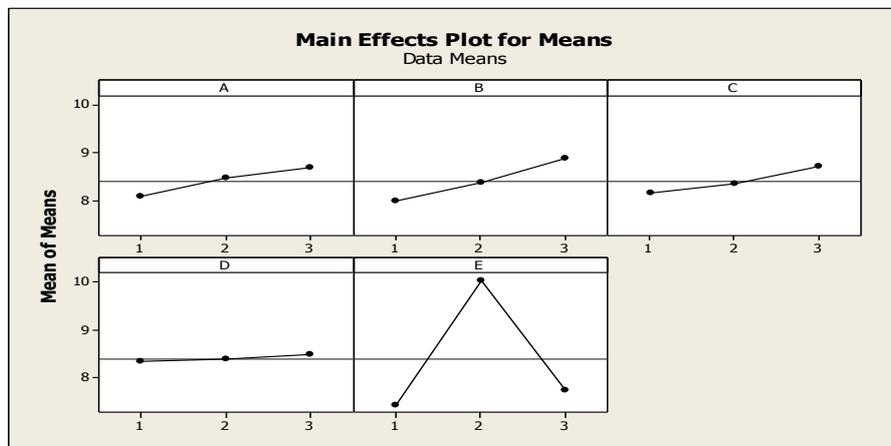


Figure 1. Main effect plot for Ra

3.2 Effect of parameters on Rt

The main effect plot for maximum height of the profile (Rt) is presented in Figure 2. From the figure it is found that the similar trend like average roughness (Ra) is also found in case of maximum height of the profile (Rt).

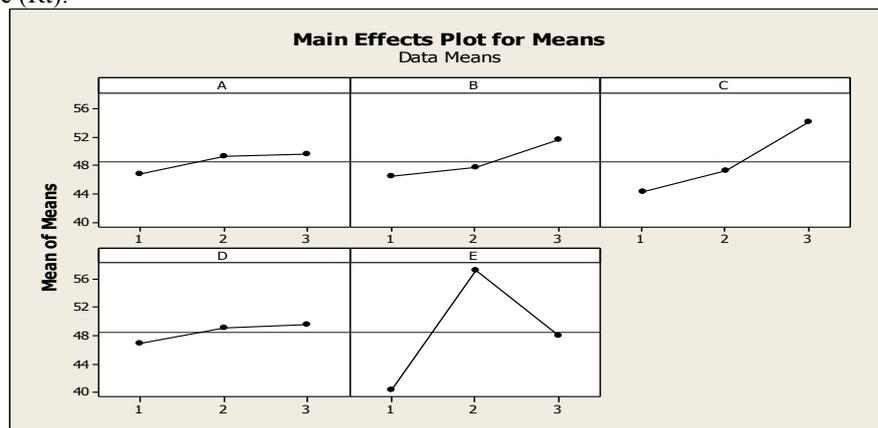


Figure 2. Main effect plot for Rt

3.3 Effect of parameters on Rz

The main effect plot for average height of the profile (Rz) is presented in Figure 3. From the figure it is found that the similar trend like average roughness (Ra) is also found in case of average height of the profile (Rz).

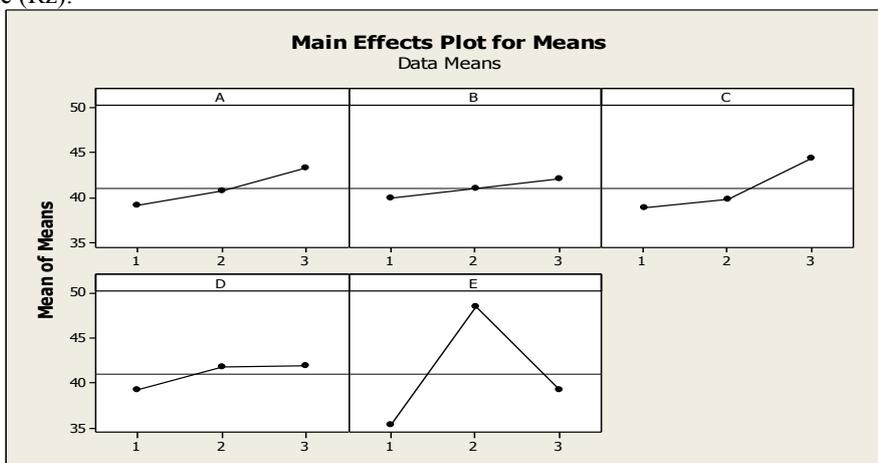


Figure 3. Main effect plot for Rz

3.4 Optimization by desirability function approach

To study all the responses concurrently, multi response optimization method i.e. desirability function approach is used. By following the procedure of desirability function approach as explain in Eqns. (4) to (7) [section 2], the individual desirability index (d_i) and overall desirability index (d_o) are calculated. The ANOVA for the overall desirability index (d_o) is tabulated in Table 3 with $R^2 = 97.5\%$. The main effect plot for the overall desirability index (d_o) are shown in Figure 4. The ANOVA is generate by the help of MINITAB 16. From the ANOVA table, the type of tool is found to be the most significant parameter followed by interaction of tool type and duty cycle, duty cycle, discharge current and voltage with percentage contribution of 61.98, 15.87, 10.94, 3.79 and 2.79 respectively. Better surface finish of EDM specimen produced with lower value of voltage (V), discharge current (I_p), duty cycle (τ) and pulse on time (T_{on}) along with the use of AlSiMg RP electrode during EDM. The optimal parametric setting is shown in response table for means of overall desirability index (Table 4).

Table 3. ANOVA for overall desirability index (d_o)

Parameters	DF	SS	MS	F	P	% Cont.
A	2	0.05266	0.026331	4.48	0.049*	2.79
B	2	0.07142	0.035709	6.08	0.025*	3.79
C	2	0.20629	0.103146	17.56	0.001*	10.94
D	2	0.01528	0.007639	1.30	0.324	0.81
E	2	1.16919	0.584594	99.52	0.000*	61.98
B*E	4	0.02517	0.006292	1.07	0.431	1.33
C*E	4	0.29944	0.074860	12.74	0.002*	15.87
Error	8	0.04699	0.005874			2.49
Total	26	1.88644				100

*Significant parameters at 95% confidence interval

Table 4. Response table for means of overall desirability index

Level	A	B	C	D	E
1	0.6701*	0.6722*	0.6955*	0.6443*	0.8179*
2	0.6027	0.6171	0.6491	0.6037	0.3269
3	0.5631	0.5465	0.4913	0.5878	0.6911
Delta	0.1070	0.1257	0.2042	0.0565	0.4909
Rank	4	3	2	5	1

*Optimal level of parametric setting

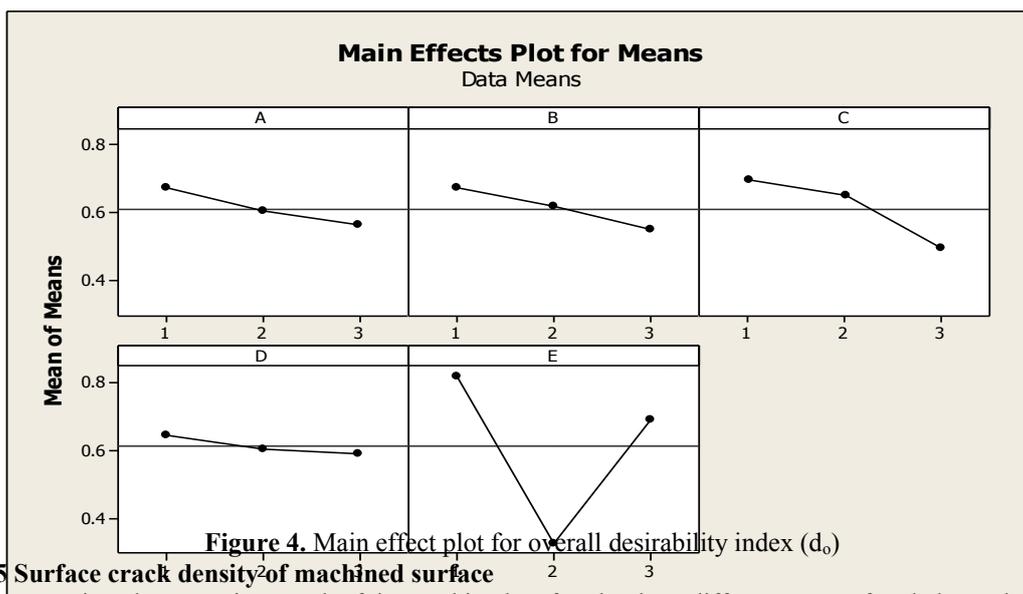
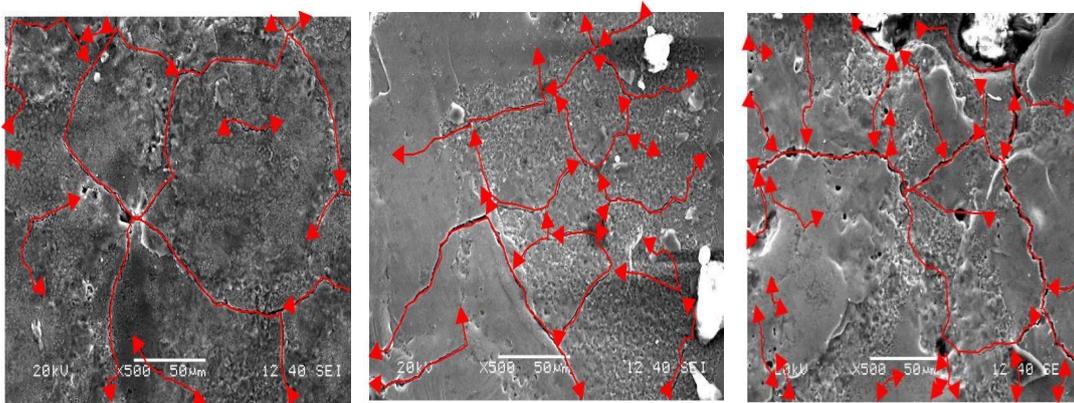


Figure 4. Main effect plot for overall desirability index (d_o)

3.5 Surface crack density²of machined surface

The scanning electron micrograph of the machined surface by three different types of tool electrodes are taken and the surface crack density (SCD) of the machined surface are measured by pdf xchange viewer

software. It is found that by the use of AlSiMg RP electrode less surface crack density is found followed by copper and graphite electrode.



(a) SCD=0.02547 $\mu\text{m}/\mu\text{m}^2$ (b) SCD=0.026526 $\mu\text{m}/\mu\text{m}^2$ (c) SCD=0.029684 $\mu\text{m}/\mu\text{m}^2$

Figure 5. Surface crack density of machined surface by different tool electrodes at parametric setting V=20V, I_p=10A, τ =67%, Ton=100 μs (a) AlSiMg RP, (b) Copper, (c) Graphite

4. Conclusion

In this work, the performance of AlSiMg electrode prepared via SLS process has been studied and compared with the performance of conventional copper and graphite electrodes. It is found that better surface finish specimens were manufactured by EDM process by taking AlSiMg SLS electrodes followed by copper and graphite electrodes respectively. By the use of desirability function approach, all the responses were converted into single response i.e. the overall desirability index (d_o) and the optimal parametric setting has been obtained for the EDM process for getting better surface finish that are V=20V, I_p=20A, τ =67%, Ton=100 μs and AlSiMg SLS tool electrode. Therefore, to get better surface finish, open circuit voltage (V), discharge current (I_p), duty cycle (τ) and pulse on time (Ton) should be minimized and AlSiMg electrode prepared via selective laser sintering (SLS) process must be used.

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