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Optimization of Electro-Discharge Coating Process using Harmony Search

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Abstract
Electro-discharge machining (EDM) is a non-traditional machining process widely used in the machining of difficult to machine materials. The EDM process is extensively used in aerospace, biomedical, die and mold making industries. In some cases, the corrosion resistance and hardness of the work piece materials are required to be improved for their applications in different environmental conditions. Coating is sometimes used to enhance the resistance property of hard materials. Coating is an extended process in EDM by the utilization of tool electrode prepared by powder metallurgy (PM) route. To meet the required applications, the electro-discharge coating (EDC) specimen must be prepared with high accuracy and excellent surface finish. In this work, the electro-discharge coating (EDC) process is performed taking AISI 1040 stainless steel as work piece and copper-tungsten prepared by powder metallurgy (PM) route as electrode. The copper-tungsten tool electrodes are prepared by varying PM process parameters like compaction pressure and sintering temperature. The EDC is performed varying different PM process parameters like compaction pressure and sintering temperature along with EDC parameters like discharge current (Ip), duty cycle (τ) and pulse-on-time (Ton). The surface roughness parameters like average roughness (Ra), maximum height of the profile (Rt) and average height of the profile (Rz) are measured by the use of surface roughness measurement machine. To reduce the number of experiments, design of experiment (DOE) approach like Taguchi L18 orthogonal array has been used. The surface properties of the EDC specimen are optimized by Taguchi based VIKOR method combined with Harmony search algorithm and the best parametric setting is reported for the EDC process. Interaction of sintering temperature and compaction pressure is found to be the significant term followed by compaction pressure. With the increase in compaction pressure, specimens with superior surface quality are produced in EDC process.

Key words: Electro-discharge coating, Powder metallurgy, VIKOR, Harmony Search, Surface roughness.

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1. Introduction

Electro-discharge coating (EDC) is an exceptional process of electrical discharge machining (EDM), where material deposition occur on the workpiece material. Coating is sometimes used to enhance the resistance property of hard materials. Coating is an extended process in EDM by the utilization of tool electrode prepared by powder metallurgy (PM) route. In EDC process, both tool electrode and workpiece are immersed inside the dielectric medium. During the EDC process, more tool wear rate occur as compare to material removal rate and deposition takes place on the workpiece with increase in the weight of the workpiece. Due to the material deposition, the wear and corrosion resistance of the workpiece material increases. The electrical discharge coated materials can be used in chemical, aerospace, automobile, tool and die industries.

TiC-Cu green compact tool electrode was used for surface modification of aluminum workpiece. The EDC process was studied by taking process parameters like peak current, pulse-on-time, composition and compaction pressure of tool electrodes with process performance like roughness, layer thickness and micro-hardness of the coated surface [1]. Copper-tungsten tool electrode prepared via powder metallurgy root was used for electrical discharge coating of workpiece materials like C-40 steel, AISI D2 steel, and Inconel 718. Here transfer of tool materials occurred with deposition of the material on the workpiece. Due the presence of hydrocarbon dielectric fluid like kerosene, tungsten carbide (WC) deposition occurred on the workpiece with increase in micro-hardness of the workpiece [2-6]. TiC-Cu tool electrodes prepared via powder metallurgy root were used in electro-discharge machining (EDM). Surface roughness of the machined surface decreased with increase in relative density of the electrodes. The best EDM performance could be found in 15% TiC addition with Cu-W electrode i.e. lowest tool wear rate, highest material removal rate and best surface finish of the machined surfaces [7-8]. Solid copper and powder compact copper tool electrodes were used to study the EDC performance on Ti-6Al-4V alloy and hardened steel. Powder metallurgy electrode produced alloying effect rather than material removal due to less strength of the compact electrodes [9-10]. Surface modification of mild steel was performed by bronze (90% copper and 10% tin) compact electrode. The material transfer occurred from the tool electrode to the work piece in reverse polarity condition [11]. Surface modification of hardened AISI D2 Sendzimir rolls was done by taking TiC-WC-Co and WC-Co electrode prepared via powder metallurgy root. There was formation of layer containing Ti and W, which increases the micro-hardness of the roll. The compaction pressure and sintering temperature increased the physical, mechanical, electrical, thermal and microstructural properties of the electrode, that lead to higher coating performance, but transfer or surface alloying was reduced [12]. Electrical discharge coating was used to improve the wear resistance of roll surface i.e. 2%Cr steel by using TiC sintered electrode. The wear resistance of TiC coated rolls by EDC was superior to that of conventional chrome-plated rolls [13]. Ceramic coating was done on the surface of aluminum by EDC with the use of green compact Ti-B_4C electrode. Different parameters like compaction pressure, composition of the electrode material, peak current and pulse duration were varied during EDC. Peak current was found to be most influential parameters. After EDC the hardness of the workpiece material was improved [14].

The EDC process was performed mainly by the use of electrodes prepared via powder metallurgy (PM) root, so that the different composition and material of the electrode can be varied as the requirement of the EDC process. For the use of the coated workpiece in chemical, aerospace, automobile, tool and die industries, the surface finish produced must be excellent. The different process of the powder metallurgy process was described by different researchers [7-8,15]. To investigate the surface roughness characteristics of the powder metallurgy (PM) electrode during EDC, copper-tungsten (Cu-W) electrode prepared via PM route was used. The PM copper-tungsten electrode were produced by varying different compaction pressure and sintering temperature. The effect of different EDC process parameters like discharge current (I_p), duty cycle (τ) and pulse on time (T_{on}) were studied along with PM process parameters.

2. Materials and Methods

In this work, copper-tungsten prepared via PM route was used as tool electrode for the EDC process by taking 1040 stainless steel as workpiece material and EDM oil as dielectric fluid. The chemical composition of 1040 stainless steel is manganese 0.75%, carbon 0.4%, sulfur 0.04%, phosphorous 0.03% and rest of ferrous. Copper and tungsten powder of 325 mesh size were taken 30% Cu and 70% W by weight. After complete mixing of the powders in pulverizing mill for 10 hours, the powder mixture was compacted in an uniaxial compaction machine with different compaction pressure by the help of the punch and die system. Then the green electrode sintered in a tubular furnace in argon environment for different sintering temperatures. The different PM process parameters varied for the preparation of the tool electrodes were listed in Table 1.

Table 1. Input parameters with different levels

Parameters	Level 1	Level 2	Level 3
A-ST(^{0}C)	700	900	-
B-CP (MPa)	100	150	200
C-I_p(A)	20	25	30
D-τ (%)	42	50	58
E-T_{on}(μs)	100	200	300

To study the effect of the copper-tungsten tool electrode different PM process parameters like compaction pressure (CP) and sintering temperature (ST) are varied along with EDC process parameters like discharge current (I_p), duty cycle (τ) and pulse-on-time (T_{on}). The values of these process parameters with different levels are listed in Table 1. To reduce the number of experiments, design of experiment (DOE) approach like Taguchi L_{18} orthogonal array has been used. The EDC process of workpiece material 1040 stainless steel by taking copper-tungsten electrode has been performed in a die sinking EDM (ELECTRA EMS 5535). To meet the required applications in the field of chemical, automobile, aerospace, biomedical, die and mold making industries the electro-discharge coating (EDC) specimen must be prepared with high accuracy and excellent surface finish. The surface roughness parameters like average roughness (Ra), maximum height of the profile (Rt) and average height of the profile (Rz) are measured by the use of surface roughness measurement machine (Taylor-Hobson-PNEUNO-Suetronic 3+). The output surface roughness values (Ra, Rt, Rz) for all the experiments along with the input parameters are listed in Table 2. Here the surface roughness values are measured for three trials for each coating specimens. The surface roughness values are optimized by Taguchi-based VIKOR method combine with Harmony Search (HS) algorithm.

Table 2. Taguchi L18 orthogonal array and output response of surface roughness parameters with VIKOR Index

Sl. No.	ST(^{0}C)	CP (MPa)	I_p(A)	DC (%)	T_{on}(µs)	Surface roughness (µm) Trial-1			Surface roughness (µm) Trial-2			Surface roughness (µm) Trial-3			VIKOR Index
	A	B	C	D	E	Ra	Rt	Rz	Ra	Rt	Rz	Ra	Rt	Rz	Qi
1	700	100	20	42	100	14.8	116	82	15.6	78	137	17	121	83	0.893
2	700	100	25	50	200	16.4	124	84	16.8	113	81	16.8	125	88	0.782
3	700	100	30	58	300	20.8	135	105	20.4	143	95	20.2	143	98	1.000
4	700	150	20	42	200	10.8	79	57	11.4	77	62	12.2	90	67	0.287
5	700	150	25	50	300	9	61	48	10.6	77	58	8.8	60	48	0.334
6	700	150	30	58	100	11	88	58	10	73	58	11.2	83	57	0.332
7	700	200	20	50	100	11.2	64	56	8.4	58	45	9.8	68	49	0.001
8	700	200	25	58	200	10	59	50	11	92	61	9.8	70	54	0.152
9	700	200	30	42	300	10.2	71	50	9.4	74	51	9.4	66	49	0.060
10	900	100	20	58	300	14.6	100	82	14	98	70	15.2	88	74	0.558
11	900	100	25	42	100	11.2	73	58	10.8	69	58	10.4	74	56	0.152
12	900	100	30	50	200	16.8	111	86	17.2	117	98	15	107	72	0.729
13	900	150	20	50	300	14.2	104	73	15.8	110	81	15.4	113	73	0.645
14	900	150	25	58	100	14.4	117	78	12.4	91	61	13	86	67	0.508
15	900	150	30	42	200	14.4	100	73	16.2	109	88	16.8	103	83	0.656
16	900	200	20	58	200	16.8	106	86	17.4	117	80	15.2	95	72	0.690
17	900	200	25	42	300	16.4	112	76	16.2	103	76	14.4	109	75	0.645
18	900	200	30	50	100	15.2	111	69	12.6	79	68	13.6	104	68	0.515

2.1 VIKOR (Vlse Kriterijumska Optimizacoja I Komopromisno Resenje) Method

The VIKOR method is an optimization process used to optimize the process parameters to increase the desire output by minimizing the undesired parameters. To convert the multi-responses into single response Taguchi-based VIKOR method has been used. The procedure of the Taguchi-based VIKOR method is as follows [16].

1. Calculate the signal-to-noise ratio (η_{ij}).

(i) For smaller is the better.

$$\eta_{ij} = -10\log[\frac{1}{n}\sum_{k=1}^{n} y^2{}_{ijk}] \qquad (1)$$

(ii) For larger is the better.

$$\eta_{ij} = -10\log[\frac{1}{n}\sum_{k=1}^{n}\frac{1}{y_{ijk}{}^2}] \qquad (2)$$

(iii) For nominal is the best.

$$\eta_{ij} = -10\log[\frac{\frac{1}{n-1}\sum_{k=1}^{n}(y_{ijk}-\overline{y_{ij}})^2}{\overline{y_{ij}}}] \qquad (3)$$

n = number of repeated experiment.

y_{ijk} = response at ith trial, jth response variable in kth replication.

$$\overline{y_{ijk}} = \frac{1}{n}\sum_{k=1}^{n} y_{ijk}$$

2. Calculate the scaled S/N ratio (Y_{ij}).

$$Y_{ij} = \frac{\eta_{ij} - \eta_j^{\min}}{\eta_j^{\max} - \eta_j^{\min}} \qquad (4)$$

$\eta_j^{\min}$ and $\eta_j^{\max}$ are the minimum and maximum S/N ratio.

3. Calculate the ideal (A^*) and negative ideal (A^-) solution.

$$A^* = \{\max Y_{ij,} i = 1,2.....n\} = \{Y_1^*, Y_2^*, ...\} \qquad (5)$$

$$A^- = \{\min Y_{ij}, i = 1,2,.....n\} = \{Y_1^-, Y_2^-, ...\} \qquad (6)$$

4. Calculate the Utility (Si) and Regret (Ri) measures for each experimental trials.

$$S_i = \sum_{j=1}^{n} \frac{w_j (Y_j^* - Y_{ij})}{(Y_j^* - Y_j^-)} \qquad (7)$$

$$R_i = Max_j \frac{w_j (Y_j^* - Y_{ij})}{(Y_j^* - Y_j^-)} \qquad (8)$$

w_j = weightage such that $\sum w_j = 1$

5. Calculate the VIKOR index of the ith experimental trial.

$$Q_i = \nu\left(\frac{S_i - S^*}{S^- - S^*}\right) + (1-\nu)\left(\frac{R_i - R^*}{R^- - R^*}\right) \qquad (9)$$

i= 1,2,3……. n,

$S^* = MinS_i$, $S^- = MaxS_i$, $R^* = MinR_i$, $R^- = MaxR_i$.

ν = weight of the maximum group utility, which is usually taken as 0.5.

2.2 Harmony Search (HS) algorithm

The Harmony Search (HS) algorithm is a musical-based metaheuristic optimization technique, which is based on jazz music. Aesthetic quality of music is developed by tuning pitch, bandwidth, timbre and amplitude [17-19]. The procedure of HS algorithm are as follows.

1. Formulate the harmony.
2. Set up the tuning parameters like pitch, bandwidth, etc.
3. Develop the objective function.
4. Develop the Harmony memory (HM) randomly.
5. Improvise harmony from the existing HM and update the HM.
6. Repeat the last two steps till the fulfillment of the termination criteria.

3. Result and Discussion

The experiment of EDC has been performed for the coating of 1040 stainless steel and the surface roughness parameters were measured as described in section 2. The surface roughness parameters like average roughness (Ra), maximum height of the profile (Rt) and average height of the profile (Rz) from Table 2 were used to calculate the VIKOR index by the procedure as given in equations

(1) to (9). The VIKOR index (Qi) also listed in Table 2. The ANOVA for the means (VIKOR index) is tabulated in Table 3 with $R^2 = 99.3\%$ and the response table for means (VIKOR index) represented in Table 4. The main effect plot for the VIKOR index are plotted in Figure 1. The ANOVA and response table were generated by using MINITAB 16. From the ANOVA table it was found that interaction of sintering temperature and compaction pressure have significant influence on surface finish followed by compaction pressure and sintering temperature. With the increase in compaction pressure, specimens with superior surface quality are produced in EDC process. Similarly, with decrease in sintering temperature good surface quality of coating surface can be produced by EDC process.

Table 3. ANOVA for Means (VIKOR index)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Cont.
A	1	0.08792	0.087920	0.087920	17.65	0.052	6.151
B	2	0.36270	0.362700	0.181350	36.41	0.027*	25.376
C	2	0.04527	0.045273	0.022637	4.55	0.180	3.167
D	2	0.02510	0.009991	0.004995	1.00	0.499	1.756
E	2	0.08415	0.042214	0.021107	4.24	0.191	5.887
A*B	2	0.73599	0.735992	0.367996	73.89	0.013*	51.493
B*C	4	0.07820	0.078201	0.019550	3.93	0.213	5.471
Residual Error	2	0.00996	0.009961	0.004980			0.699
Total	17	1.42930					100

*Significant at 95% confidence interval.

Table 4. Response Table for Means (VIKOR Index)

Level	A	B	C	D	E
1	0.4267	0.6857	0.5122	0.4488	0.4000
2	0.5664	0.4603	0.4288	0.5008	0.5493
3	-	0.3437	0.5487	0.5400	0.5403
Delta	0.1398	0.3420	0.1198	0.0912	0.1493
Rank	3	1	4	5	2

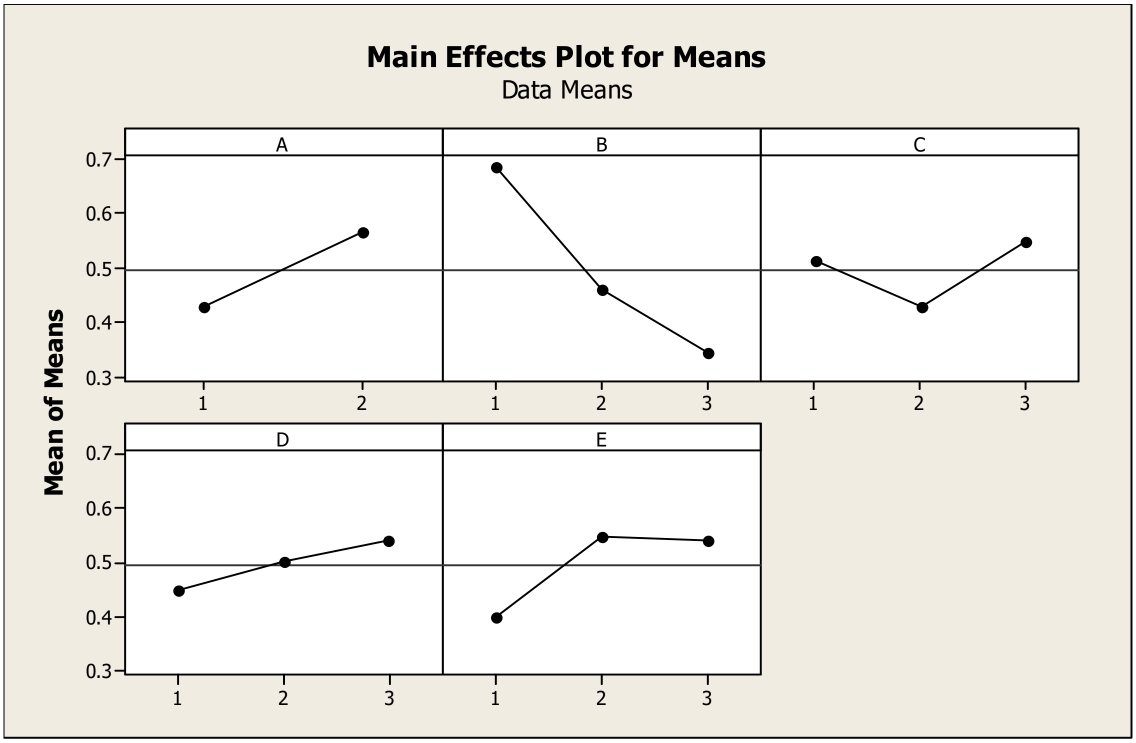

Figure 1. Main Effects Plot for Means

A non-linear regression analysis has been done between the VIKOR Index and parametric inputs responses values were expressed in the equation (10) is represented by f(x) having R^2 value of 83.7%. The non-linear regression equation has been generated by using SYSTAT 13. This non-linear equation is used as objective function in the HS algorithm and the optimal setting has been found. The optimum parametric setting for the VIKOR method and HS algorithm are listed in Table 5. The Graph of fitness value vs. number of iteration is given in Figure 2. The Taguchi based VIKOR method combine with HS algorithm given better result as compare to Taguchi based VIKOR method.

$$f(x) = 0.029\,A^{0.457}\,B^{-0.884}C^{0.334}D^{0.432}E^{0.269} \qquad (10)$$

Table 5. Optimum parametric setting for the VIKOR method and HS algorithm

Method	ST	CP	Discharge current	Duty cycle	Pulse-on-time	Fitness value
VIKOR	700^0C	200MPa	25A	42%	100µs	0.2720526
HS	700.0001^0C	200MPa	20A	42%	100µs	0.2525137

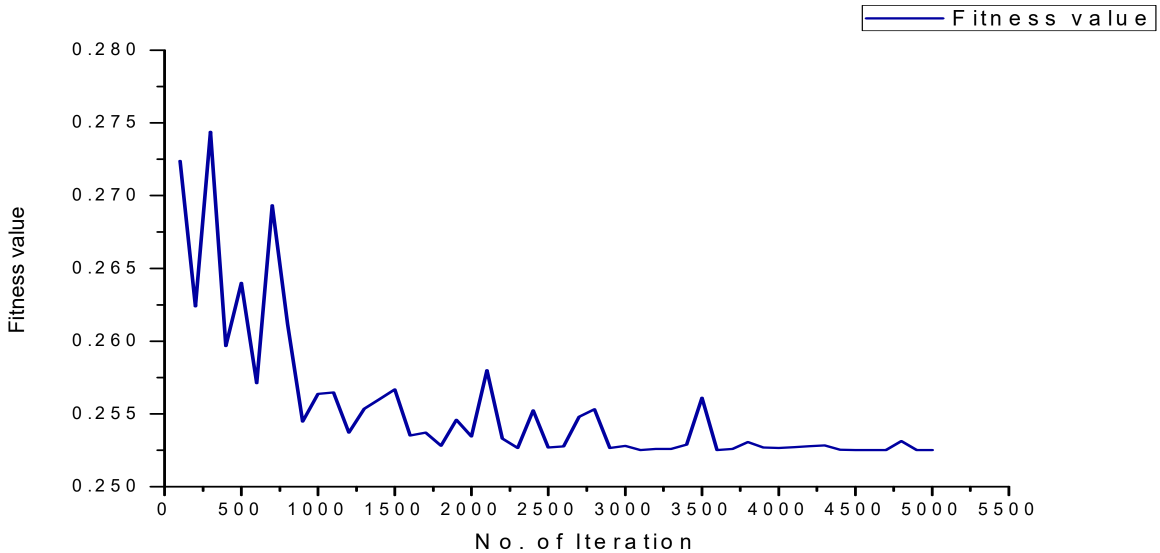

Fig 2. Graph of Fitness value vs. number of iteration

4. Conclusion

In this EDC process attempts have been made to study the influence of process parameters on the surface finish properties of the coated specimen. By the use of Taguchi-based VIKOR method all the responses were converted into single response i.e. the VIKOR Index. Finally, HS algorithm has been used to determine the optimal parametric setting for the EDC process for getting better surface finish. The Taguchi based VIKOR method combine with HS algorithm given better result as compare to Taguchi based VIKOR method. To get better surface finish the compaction pressure should be maximized and sintering temperature should be minimized.

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