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STATISTICAL ANALYSIS OF ELECTROCHEMICAL DISCHARGE MACHINING FOR SODA LIME GLASS

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ABSTRACT:

Electro chemical discharge machining (ECDM) is a hybrid process which combines the features of electro chemical machining (ECM) and electro discharge machining (EDM).The need for micromachining of advanced engineering materials started increase in demand in various sectors like nuclear, aerospace and medical industries. Electrochemical discharge machining (ECDM) technique is that involves high-temperature melting and accelerated chemical etching under the high electrical energy discharged and has potential to machine electrically non-conductive materials such as glass, quartz, composite, ceramics. In ECDM, gas film and sparks are generated on a tool when voltage is applied between the tool and a counter electrode. Work-piece materials are removed mainly by the heat of the sparks. The spark generation is affected by both the voltage and electrolyte conditions. In this present work, The effect of process variables such as electrolyte concentration (EC), duty factor (DF), voltage (V), on response parameters such as Material Removal Rate (MRR), Tool Wear Rate (TWR), Diametric overcut (DOC) have been investigated soda-lime glass in electrochemical discharge machining (ECDM) using tungsten carbide electrode. Analysis of variance (ANOVA) and F-test were performed to determine the significant parameters at a 95% confidence interval.

KEYWORDS: Electrochemical Discharge Machining, Material Removal Rate, Soda-Lime Glass, Tool Wear Rate.

I. INTRODUCTION:

Nonconventional machining processes can be defined as the use of chemical, mechanical, thermal, electrical or combinations of these energies processes to machine a work-piece and remove material without contact between work-piece and tool material. Electrochemical discharge machining (ECDM) is a non-traditional machining method that has been firstly introduced for glass micro drilling by kurafuji and Suda in 1844[1]. This process is mainly used for micro-machining of hard and brittle non-conductive materials such as glass, ceramic, refractory bricks, quartz and composite materials. This has attracted extensive research interests because of additional advantage of machining electrically non-conductive materials.

The ECDM process consists of a cathode tool and an anodic work piece, which are separated by a gap filled with electrolyte (which is Depending upon the tool and work piece material, the commonly used electrolytes are NaOH, NaCl, KOH, $NaNO_3$, HCL, H_2SO_4, NaF etc.) and pulsed direct current (DC) power applied between them. And connected to a D.C. power supply, consequently when a voltage higher than a critical value is applied, electrolysis in the solution starts and hydrogen bubbles grow so dense on the tool electrode (cathode) that they coalesce into a gas film. The gas film acts as an insulating layer around the tool and provides electrical potential difference between the tool and electrolyte. This leads to electrical discharges between the electrodes, thus achieving both electro chemical dissolution and electro discharge erosion of the workpiece [1]. Figure 1 shows the principle of ECDM.

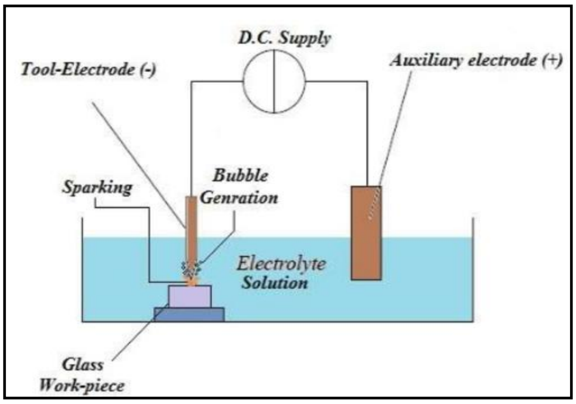

Fig. 1.2 Schematic diagram of the ECDM

The electrochemical reaction for soda-lime glass workpiece ECDM is,

$SiO_2 + 2NaOH = Na_2O - SiO_2 + H_2O$

The sodium ion (Na^+) and the hydroxide ion (OH^-) in the electrolyte are adsorbed on the glass surface; the -Si-O-Si- bond is broken and changed into the -Si-O-Na- bond.

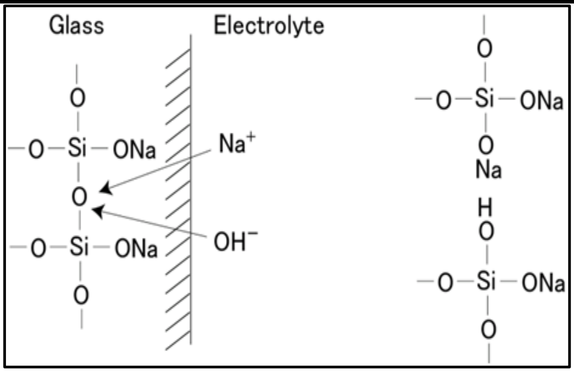

Figure 2 chemical reaction of soda-lime glass workpiece

The performance of the process depends on many parameters like tool-electrode material, electrode size and shape, weld ability characteristic of tool-electrode, feed-rate, work-piece material, applied voltage, current, duty cycle, pulse duration, electrolyte, its concentration and temperature, gap between tool-electrode and workpiece, distance between cathode and anode, anode material, etc.

II. LITERATURE SARVEY:

B. Mallick, M.N. Ali, B. R. Sarkar, B. Doloi, B. [1] (2014) - They carried out experimentation and presented parametric analysis, that ECDM can be used with great potential to machine electrically non-conducting harder brittle materials such as glass and can also be employed for micro-channel cutting applications. They draw the following conclusions ECDM system. Baoyang Jiang, Shuhuai Lan, Jun Ni, Zhaoyang Zhang [2] (2014) – studied the process modeling of ECDM with respect to spark generation and material removal. Tapered tool electrodes were employed as tool electrode whereas energy distribution curve and finite element method was used to study the outputs for spark generation and material removal rate. They concluded as tapered tool improved the consistency of spark generation and suppressed the generation of minor discharge sprediction of material removal is reasonable in terms of diameter and maximum depth of machined holes.Y.S. Laio, L.C. Wu, W.Y. Peng [3] (2013) - They studied the effects of Sodium Dodecyl Sulphate (SDS) surfactant added electrolyte on machining quartz in electrochemical discharge machining (ECDM). Experimental results show that, as current density is increased, there is more bubble release around the electrode. The sparks become brighter and take place in a larger area and more stable pulse current is obtained. As a result, a less taper and a better quality but a little over size hole can be drilled with a higher engraving speed. Based on the observation of sparking process together with the experimental results, a new bubble forming mechanism during ECDM when SDS added electrolyte used is inferred. Bhattacharyya and m. Malapati (2004) – in this paper, the advantages of ECDM over other machining process as absence of burr, bright surface finish and ability to machine complex shapes regardless of its hardness is expressed. They also found that, the material for tool should be chemically inert and should have good electrical conductivity. Need to use freash electrolyte everytime is essential because precipitate of electrolyte may damage the tool and will affect MRR. Flow of electrolyte has effect on machining accuracy.

III. EXPERIMENTAL SETUP:

For this experimentation, we have selected Soda-lime glass as a work piece material. Tungsten Carbide with cylindrical geometry is used as a cathode tool. All experiments has been carried out on ECDM machine. For work-piece and tool preparation we used diamond cutter and cylindrical grinder. In pre-processing the work pieces and tools were weighing on the Citizon AX 220 digital weighing machine. It is having a least count of 0.1 mg. After machining had done, again we measured weights of tools and work-pieces on same machine for calculation of material removal rate and tool wear rate values. For diametric overcut, diameter of tool is measured by Digital Venire Caliper and diameter of hole of work-pieces is measured on Machine vision measuring system unit.

Table.4.1 Chemical Composition of soda-lime glass

Elements	SiO_2	Na_2O	CaO	MgO	Al_2O_3	K_2O	SO_3
Weight %	72	13	10.5	2.4	0.6	0.4	0.3

Table 4.2 Physical Properties of soda-lime glass

Youngs Modulus (psi)	9.8 ×106
Coeff. Of Expansion	89 × 10-7 cm/cm/ oC
Poisson Ratio	0.22
Density (mg/mm3)	2.52 g/cm3
Hardness (Mohs)	5.5
Strain Point	511 ˚ C
Anneal Point	545 ˚ C
Soften Point	724 ˚ C

Sodium Dodecyl Sulphate also known as sodium laurel sulphate and it is a surfactant have long chain alkyl (like fatty acid, etc.) is lipophilic group.

PHYSICAL AND CHEMICAL PROPERTIES:

Melting Point – 2870˚ c
Boiling Point – 6000˚ c
Density -15.6 g/cm^3
Thermal conductivity -28 W/m.k
Poisson Ratio- 0.2
Weight (%)- Tungsten 94%, Cobalt 6%

In electrochemical discharge machining, electrolyte is very reactive with metal. So we designed the machining chamber made of Acrylic material and bonded with chloroform which is chemically not reactive with

NaOH and transparent enough to see level of electrolyte when poured in it. Special slider fixture made of SS (which is non-corrosive with NaOH electrolyte) material designed in chamber with allen bolt to fix work-piece in it. The chamber dimensions are (100 × 100 ×80) mm having 8 mm thickness. The figure shows the acrylic chamber.[5]

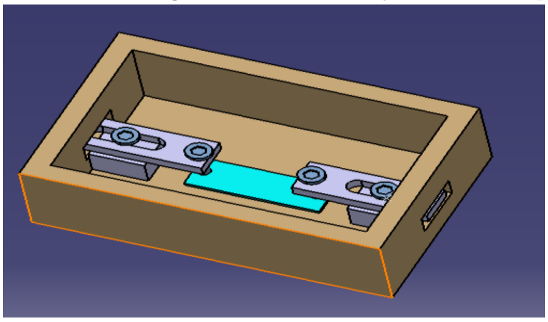

Fig.4.5Catia model of acrylic chamber

IV. EXPERMIENTAL CONDITIONS:

Following machining parameters are kept constant selected on performance characteristics,

Sr. No.	Machining Condition	Specification
1	Work-piece material	Soda-lime Glass
2	Tool electrode material	Tungsten Carbide
3	Auxiliary tool material	Nickel
4	Machining time	20 min
5	Level of electrolyte	1 mm (above w/p)
6	Distance between anode to cathode	45 mm
7	Tool feed rate	1.67 µm/sec
8	Area ratio anode to cathode	50:1
9	Gap between cathode tool and workpiece	25 µm
10	Temperature	Ambient 27° C

With reference to literature survey, the following parameters were considered as variable input parameters,

1. VOLTAGE (V): The D.C voltage is applied between cathode and anode from D. C. power supply system.

2. DUTY FACTOR (%): The ratio of the pulse on time to the pulse on and pulse off time (total pulse time) is called as duty factor.

3. ELECTROLYTE CONCENTRATION (wt %): It is expressed in % by wt, which indicates the weight of the NaOH dissolved per 100 ml demineralised water to prepare the aqueous electrolyte.

The decision variables were,

1. MRR (MG/MIN): Material removal rate is calculated by taking weight work-piece before and after the machining and dividing it by machining time. Or “the ratio of the volume of material removed from the work-piece with respect to the machining time”

MRR (mg/min) $= \frac{initial\ wt.of\ workpiece\ - final\ wt.\ of\ workpiece}{time}$

2. TOOL WEAR RATE (MG/MIN) – Tool wear rate is calculated by taking weight tool before and after the machining and dividing it by machining time. Or “the ratios of the volume of material wear from the tool surface with respect to the machining time”

TWR (mg/min) = $\frac{initial\ wt.of\ tool - final\ wt.\ of\ tool}{time}$

3. DIAMETRIC OVER CUT (MM) - It is the difference between machined hole diameter and tool diameter. It is measured on vision machine system.

DOC (mm) = Diameter of Hole – Diameter of Tool

As discussed above, the different input parameters were selected from the literature survey. The variation in the input parameters is done to carry out the experimentation and plackett burman method of design of experiment is selected to run the experiments. Following table shows the combination and runs.

Table 4.5Plackettburman design of experiment plan

Std Order	Run Order	PtType	Blocks	Volt	Duty Factor	Elec.Conc
4	1	1	1	75	75	35
5	2	1	1	75	85	25
10	3	1	1	75	75	25
1	4	1	1	75	75	35
11	5	1	1	65	85	25
6	6	1	1	75	85	35
3	7	1	1	65	85	35
12	8	1	1	65	75	25
2	9	1	1	75	85	25
7	10	1	1	65	85	35
9	11	1	1	65	75	25
8	12	1	1	65	75	35

After conducting various trails experiments, operating range and levels of input parameters have been finalized.

Table 4.6 Levels selected for experiment

Parameters	Levels		
	Level 1	Level 2	Level 3
Electrolyte Concentration ‘EC’ (gm/l)	25	30	35
Duty Factor ‘DF’ (%)	75	80	85
Applied voltage ‘V’ (V)	65	70	75

For design of experiment MINITAB 17 software was used. For experimentation RSM Box behnken technique was used.

Table 4.7 DOE plan for experimentation

Std Order	Run Order	Pt Type	Voltage	Duty Factor	Elect. Conc
9	1	2	70	75	25
14	2	0	70	80	30
8	3	2	75	85	30
2	4	2	75	80	25
13	5	0	70	80	30
4	6	2	75	80	35
12	7	2	70	85	35
11	8	2	70	85	25
1	9	2	65	80	25
7	10	2	65	85	30
6	11	2	75	75	30
5	12	2	65	75	30
10	13	2	70	75	35
15	14	0	70	80	30
3	15	2	65	80	35

For machining chamber the material chosen was acryalic because it is transparent in nature so that level of electrolyte can be easily detected. In addition to this it does not react with NaOH solution.

V. RESULTS AND DISCUSSION:

After experimentation was carried by using Box behenken RSM methodology results of response parameters such as MRR, TWR, and DOC are noted down as follows.[7,8]

Std Order	Run Order	Pt	Volta ge	Duty Facto r	Elec. Conce	MRR (mg/ min)	TWR (mg/ min)	DOC (mm)
9	1	2	70	75	25	0.48	1.85	0.1728
14	2	0	70	80	30	0.51	1.965	0.2432
8	3	2	75	85	30	0.61	2.2	0.1322
2	4	2	75	80	25	0.58	2.35	0.2025
13	5	0	70	80	30	0.51	1.97	0.2257
4	6	2	75	80	35	0.68	2.45	0.2576
12	7	2	70	85	35	0.59	2.23	0.1457
11	8	2	70	85	25	0.45	1.995	0.1808
1	9	2	65	80	25	0.215	1.85	0.1767
7	10	2	65	85	30	0.32	1.9	0.192
6	11	2	75	75	30	0.67	2.35	0.3239
5	12	2	65	75	30	0.395	1.675	0.2372
10	13	2	70	75	35	0.53	2.15	0.3921
15	14	0	70	80	30	0.515	1.955	0.2457
3	15	2	65	80	35	0.45	2.04	0.2174

OPTIMISATION OF RESPONSE PARAMETERS BY TOPSIS METHOD:

The Technique for Order of Preference by Similarity to ideal Solution (TOPSIS) is a multi-criteria decision analysis method and make ranks the alternatives according to their distances from the ideal and the negative ideal solution, i.e. the best alternative has simultaneously the shortest distance from the ideal solution and the farthest distance from the negative ideal solution. The ideal solution is identified with a hypothetical alternative that has the best values for all considered criteria whereas the negative ideal solution is identified with a hypothetical alternative that has the worst criteria values. In practice, TOPSIS has been successfully applied to solve selection or evaluation problems with a finite number of alternatives because it is intuitive and easy to understand and implement.[6]

Following steps involved for calculating the TOPSIS values are as follows:[7]

Step 1: This step involves the development of matrix format. The row of this matrix is allocated to one alternative and each column to one attribute. The decision making matrix can be expressed as:

$$\mathbf{D}=\begin{matrix} A_1 \\ A_2 \\ \cdot \\ A_i \\ \cdot \\ A_m \end{matrix}\begin{bmatrix} x_{11} & x_{12} & \cdot & x_{1j} & x_{1n} \\ x_{21} & x_{22} & \cdot & x_{2j} & x_{2n} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ x_{i1} & x_{i2} & \cdot & x_{ij} & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ x_{m1} & x_{m2} & \cdot & x_{mj} & x_{mn} \end{bmatrix} \quad \textbf{(i)}$$

Here, *i A* ((*i*=1, 2,.......,*m*) represents the possible alternatives; *x* (*j n*) *j* =1, 2,........, represents the attributes relating to alternative performance, *j* =1, 2,.........., *n* and *ij x* is the performance of *i A* with respect to attribute X_j.

Step 2: Obtain the normalized decision matrix N_{ij}.This can be represented as:

$$N_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad \textbf{(ii)}$$

Here, N_{ij} represents the normalized performance of A_i with respect to attribute X_j

Step 3: The weighted normalized decision matrix is constructed by multiplying the normalized decision matrix by its associated weights. The weight of each attribute was assumed to be

wj(j = 1,2, . . ., n).

$\mathbf{W_{ij}}$**=** **N**ijxWj **(iii)**

Where w_j is the weight value of the j^{th} criterion, and

$$\sum_{j=1}^{n} w_j = 1$$

Step 4: Determine the positive-ideal solution A^+ and the negative-ideal solution A^-.

$$A^+ = \{(w_1^+, w_2^+, \cdots, w_n^+)\} = \{(\max_i w_{ij} \mid j \in S_B), (\min_i w_{ij} \mid j \in S_C)\}$$

$$A^- = \{(w_1^-, w_2^-, \cdots, w_n^-)\} = \{(\min_i w_{ij} \mid j \in S_B), (\max_i w_{ij} \mid j \in S_C)\} \quad \textbf{(iv)}$$

and (v)

Where S_B and S_C denote the set of benefit criteria and set of cost criteria respectively.

Step 5: Calculate Euclidean distance.

$$s_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2}, \forall i \in I.$$

(vi)

$$s_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}, \forall i \in I. \quad \textbf{(vii)}$$

Step 6: Calculate the relative closeness to the ideal solution

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C $R_i = \dfrac{s_i^-}{s_i^+ + s_i^-}$, for $i \in I$.

(viii)

Step 8: Rank the preference order.

For ranking alternatives by using this index, we can choose the best alternative with the maximum value of relative closeness.

The following procedures are used to select the best alternatives from multi-criterion TOPSIS method.

Step 1: The objective and the important evaluation attributes are determined. For this particular problem MRR is considered as a beneficial attribute and others are considered as non-beneficial attributes (i.e.) minimization

Step 2: All the information available is represented in the form of a DM

Table 6.2 Decision matrix for ECDM

Run Order	MRR	TWR	DOC
1	0.48	1.85	0.1728
2	0.51	1.965	0.2432
3	0.61	2.2	0.1322
4	0.58	2.35	0.2025
5	0.51	1.97	0.2257
6	0.68	2.45	0.2576
7	0.59	2.23	0.1457
8	0.45	1.995	0.1808
9	0.215	1.85	0.1767
10	0.32	1.9	0.192
11	0.67	2.35	0.3239
12	0.395	1.675	0.2372
13	0.53	2.15	0.3921
14	0.515	1.955	0.2457
15	0.45	2.04	0.2174

For that, the responses which are to be minimized

Use m_{ij}= max x_j-x_{ij}i =1, 2,3……….m. Number of runs.

j =1, 2, 3…………n. Number of responses.

In above input data, DOC and TWR are to be minimized so we have to use above formula for TWR, and DOC.

Max x_i =2.45 for TWR and x_i = 0.3921

So we get, For TWR 2.45 -1.85=0.6 and for DOC 0.3921- 0.1728= 0.2193. So on modified decision matrix shows as follows,

Table 6.3 Modified Decision matrix for ECDM

Run Order	MRR(mg/min)	TWR(mg/min)	DOC(mm)
	X_{ij}	X_{ij}	X_{ij}
1	0.48	0.6	0.2193
2	0.51	0.485	0.1489
3	0.61	0.25	0.2599
4	0.58	0.1	0.1896
5	0.51	0.48	0.1664
6	0.68	0	0.1345
7	0.59	0.22	0.2464
8	0.45	0.455	0.2113
9	0.215	0.6	0.2154
10	0.32	0.55	0.2001
11	0.67	0.1	0.0682
12	0.395	0.775	0.1549
13	0.53	0.3	0
14	0.515	0.495	0.1464
15	0.45	0.41	0.1747
Sun	$\sum x^2$ij=3.97	$\sum x^2$ij=2.92	$\sum x^2$ij=0.49
Square Root	1.9935	1.7116	0.7013

From Eq. (2) the decision matrix is ***D***15×3.

Step 3: The normalized matrix ***Nij***is determined by using the following formula.

$$N_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$$

The normalized decision matrix, $\boldsymbol{N}_{18\times3}$, is calculated using above Eq. given as,

Table 6.4 Normalized Decision matrix for ECDM

Run	MRR(mg/min)	TWR(mg/min)	DOC(mm)
	N_{ij}=xij /($\sum$ x²ij)	N_{ij}=xij /($\sum$ x²ij)	N_{ij}=xij /($\sum$ x²ij)
1	0.240775	0.350536	0.3126689
2	0.255824	0.28335	0.21229548
3	0.305986	0.146057	0.3705547
4	0.290937	0.058423	0.27032386
5	0.255824	0.280429	0.23724626
6	0.341099	0	0.19176455
7	0.295953	0.12853	0.35130696
8	0.225727	0.265823	0.30126283
9	0.107847	0.350536	0.30710844
10	0.160517	0.321324	0.28529433
11	0.336082	0.058423	0.09723675
12	0.198138	0.452775	0.22085003
13	0.265856	0.175268	0
14	0.258332	0.289192	0.20873108
15	0.225727	0.239533	0.24908006

Above table shows the Normalized decision matrix ***N***18×3.

Step 4: The weighted normalized decision matrix is constructed by multiplying the normalized decision matrix by its associated weights. The weight of each attribute was drawn by AHP method be w_j(j = 1,2, . . ., n).

W_{ij}= NijxW$_J$

The weighted normalized value $W_{15\times3}$ is calculated using is given as

Table 6.5 Weighted Normalized Matrix for ECDM

Run	MRR (mg/min)			TWR (mg/min)			DOC (mm)		
	N_{ij}	W_j	Wij	N_{ij}	W_j	Wij	N_{ij}	W_j	Wij
1	0.24077	0.45	0.108349	0.35053	0.23	0.08062	0.31266	0.32	0.10005
2	0.25582	0.45	0.115121	0.28335	0.23	0.06517	0.21229	0.32	0.06793
3	0.30598	0.45	0.137693	0.14605	0.23	0.03359	0.37055	0.32	0.11857
4	0.29093	0.45	0.130922	0.05842	0.23	0.01343	0.27032	0.32	0.08650
5	0.25582	0.45	0.115121	0.28042	0.23	0.06449	0.23724	0.32	0.07591
6	0.34109	0.45	0.153494	0	0.23	0	0.19176	0.32	0.06136
7	0.29595	0.45	0.133179	0.12853	0.23	0.02956	0.35130	0.32	0.11241
8	0.22572	0.45	0.101577	0.26582	0.23	0.06113	0.30126	0.32	0.09640
9	0.10784	0.45	0.048531	0.35053	0.23	0.08062	0.30710	0.32	0.09827
10	0.16051	0.45	0.072233	0.32132	0.23	0.07390	0.28529	0.32	0.09129
11	0.33608	0.45	0.151237	0.05842	0.23	0.01343	0.09723	0.32	0.03111
12	0.198	0.4	0.0891	0.452	0.2	0.104	0.220	0.3	0.070

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	13	5	62	77	3	13	85	2	67
13	0.265 85	0.4 5	0.1196 35	0.175 26	0.2 3	0.040 31	0	0.3 2	0
14	0.258 33	0.4 5	0.1162 49	0.289 19	0.2 3	0.066 51	0.208 73	0.3 2	0.066 79
15	0.225 72	0.4 5	0.1015 77	0.239 53	0.2 3	0.055 09	0.249 08	0.3 2	0.079 70

Step 5: Determination of the positive ideal solution (A^{**}) and the negative ideal solution (A^*). These are calculated by using Eq. (4) and Eq. (5):

Table 6.6 PIS and NIS values

IPS(A^{**})	0.153494	0.10413832	0.118578
NIS(A^*)	0.048531	0	0

Step 6: The separation measure is calculated.

Table 6.7 Euclidean distance and Relative closeness to the ideal solution

Sr. No	S_i^+	S_i^-	$C^*=(S_i^- / S_i^+ + S_i^-)$
1	0.054168	0.141736	0.72349662
2	0.074537	0.11531	0.60738487
3	0.072293	0.152115	0.67784968
4	0.098818	0.120215	0.54884449
5	0.06974	0.119824	0.63210537
6	0.11882	0.121585	0.50575115
7	0.077539	0.143795	0.64967401
8	0.070965	0.125879	0.63948812
9	0.109464	0.127114	0.53730266
10	0.090895	0.119826	0.56864731
11	0.126021	0.108154	0.46185015
12	0.08021	0.13225	0.62247234
13	0.138856	0.081736	0.37053126
14	0.074056	0.116066	0.61048137
15	0.081314	0.110463	0.57599777

Step 7 Relative closeness of a particular alternative to the ideal solution:

It can be expressed in this step as follows.

$C_1^* = [0.141736/(0.054168+0.141736)] = 0.72349662$

$C_2^* = [0.11531/(0.074537+0.11531)] = 0.60738487$

And so on and given to decreasing order.

Table.6.8Ranking of relative closeness of ECDM

Sr.No	C*	Ranking
1	0.72349662	1
2	0.67784968	3
3	0.64967401	7
4	0.63948812	8
5	0.63210537	5
6	0.62247234	12
7	0.61048137	14
8	0.60738487	2
9	0.57599777	15
10	0.56864731	10
11	0.54884449	4
12	0.53730266	9
13	0.50575115	6
14	0.46185015	11
15	0.37053126	13

From the above table 6.8 it can be seen that the experimental run # 1 is the best multiple performance characteristics having highest preference order, hence it is optimum setting followed by run # 3 and # 7 for electrochemical discharge machining.

Optimum setting of parameter		
Voltage (Volt)	Electrolyte Concentration (wt %)	Duty Factor (%)
70	35	85

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