EFFECT OF ELECTROLYTES ON SURFACE INTEGRITY IN ELECTROCHEMICAL HONING PROCESS

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Abstract: *Electrochemical Honing (ECH) is a process of precision finishing of functional surfaces with the use of the electrical and mechanical energy. It is reported that the 90 percent of the material is removed by electrochemical machining (ECM) process and remaining 10 percent by mechanical scrubbing, which shows the electrical energy is the main constituent in the ECH process. Basically, electrical energy is combined with chemical to form an etching reaction to remove material from the workpiece surface. The electrolyte is pumped through the gap between the tool (cathode) and the workpiece (anode) while a continuous DC current is passed through the cell at a low voltage, so as to dissolve metal from the workpiece. Electrolytes are substances that become ions in solution and acquire the capacity to conduct electricity. The electrolyte has three main functions in the electrochemical machining (ECM) zone. It carries the current between the tool and the workpiece, it removes the product of the reaction from the cutting region, and it removes the heat produced by the current flow in the operation. Electrolytes must have high conductivity, low toxicity and corrosivity, and chemical and electrochemical stability. The rate of material removal in ECM is governed by Faraday's laws and is function of current density. Primary variables that affect the current density and MRR are voltage, feed rate, electrolyte conductivity, electrolyte concentration/composition, electrolyte flow rate and material of the workpiece. Therefore, electrolyte must be selected carefully for better outcomes.*

Key words: *ECH, Electrolyte Composition, Electrolyte Concentration, EN52, Ti6Al4V, Surface Finish*

1. INTRODUCTION

Electrochemical honing (ECH) is largely operated on the principle of electrolysis and can be thought of as highly accelerated and controlled corrosion. The main advantages of this process are the complex 3D geometries can be finished with a single setting, high rates of finishing which are virtually independent of material hardness, remove material without heat, and precise surface finish because material is removed at an atomic level [1]. In today's high precision and time sensitive scenario, ECH has wide scope for applications. More specifically, ECH is a process based on the controlled anodic dissolution of the workpiece anode, with the tool as the cathode, in an electrolytic solution. The electrolyte flows between the electrodes and carries away the dissolved metal [2].

Since the first introduction of ECH in 1967 by Randlett and Ellis, its applications have been increasingly recognized for its potential for finishing, while the precision of the finished profile is a concern of its application [3, 4]. During the ECH process, electrical current passes through an electrolyte solution between a cathode tool and an anode workpiece. The workpiece is eroded in accordance with Faraday's law of electrolysis [5]. ECH processes find wide applicability in areas such as aerospace, automobile, gear manufacturing, nuclear reactor applications, etc. Furthermore, it has been reported that the accuracy of finishing can be improved by the use of pulsed

DC and controlling various process parameters [6]. Amongst the often considered parameters are electrolyte concentration, voltage, current and inter-electrode gap [7]. Though there is a possibility of improving the precision of work, the dependency of accuracy on numerous parameters demand that a thorough investigation should be carried out to ascertain the causality to different parameters. From the available literature it can concluded that no work has been reported on the effect of electrolytes on the surface integrity in the ECH process. Therefore, the aim of the present work has to explore the use of various combinations of electrolytes ($NaCl+NaNO_3$; NaCl+KBr) of ECH process, for different workpiece material such as EN52 and Ti-6Al-4V. The process performance was compared in terms of percentage improvement in surface roughness and geometrical accuracy. In addition, workpiece surface topography aspects after processing through ECH using different electrolyte and their varying composition are critically discussed.

2. ELECTROCHEMICAL HONING (ECH) PROCESS PRINCIPLE

The process principle of ECH is based on the Faraday's laws of electrolysis and mechanical scrubbing. Figure 1 describes the proposed working principle of ECH process of clad surface of engine valve face. In this process most of the metal is removed at the atomic scale by anodic dissolution. Moreover, the honing action as well acts as performance multiplier.

In ECH, the workpiece is made as an anode and the tool is made as a cathode by applying a small DC electric potential across them. The inter-electrode gap (IEG) is filled with the full streams of electrolyte and a continuous DC current is passed through the gaps. During the process of material removal from the workpiece, oxygen is evolved out at cathode after dissolution of aqua solution and this oxygen reacts with anodic workpiece surface to form a thin metal oxide micro-film on the workpiece. This micro-film is insulating in nature and protects the workpiece surface from being further removed and it minimizes the ECM action. This oxide layer on the surface of the workpiece is scraped by the honing action, when it comes in contact with the abrasive honing tool. The honing tool was spring loaded and help to scrub the complete workpiece surface. This scrubbed surface, when returning to the ECM zone, is removed electrochemically once again. As the process carries on, the geometric accuracy and surface integrity of the workpiece surface is rapidly improved.

3. EFFECT OF NaCl AND $NaNO_3$ ELECTROLYTE

The effect of NaCl and $NaNO_3$ electrolyte combination under the various compositions

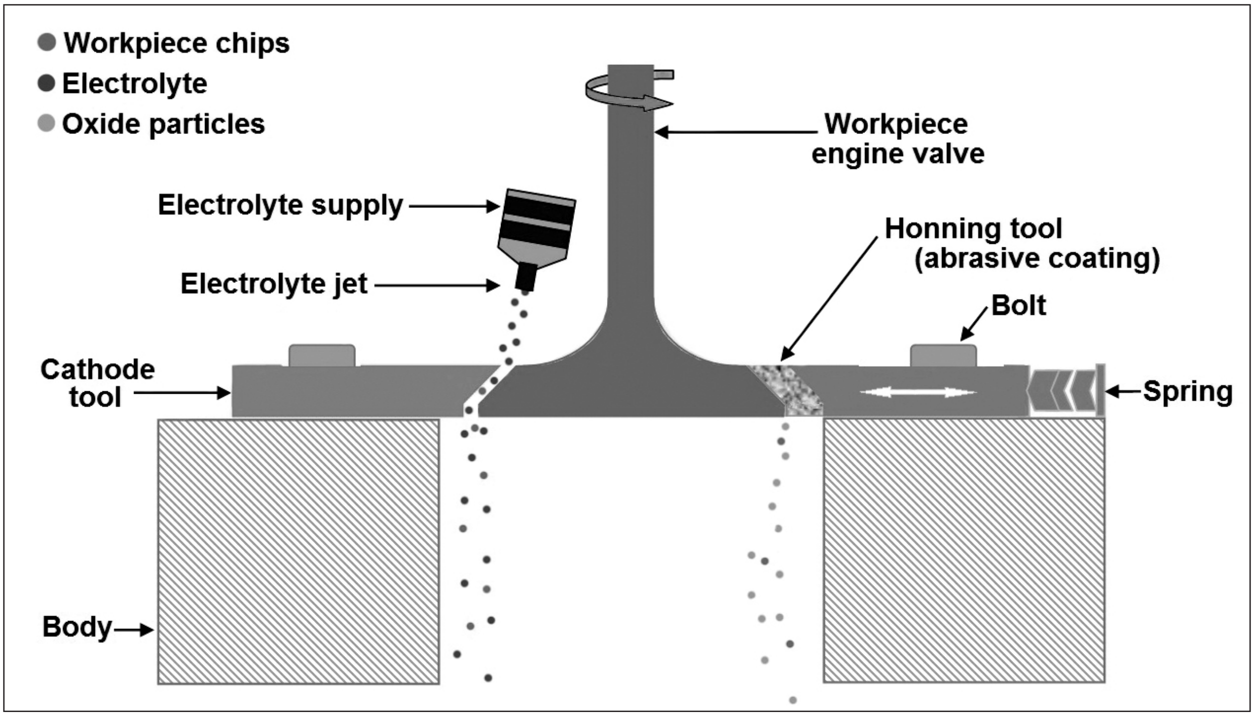

Fig 1. A Schematic of the Proposed Working Principle of ECH of Clad Surfaces of Engine Valve Face

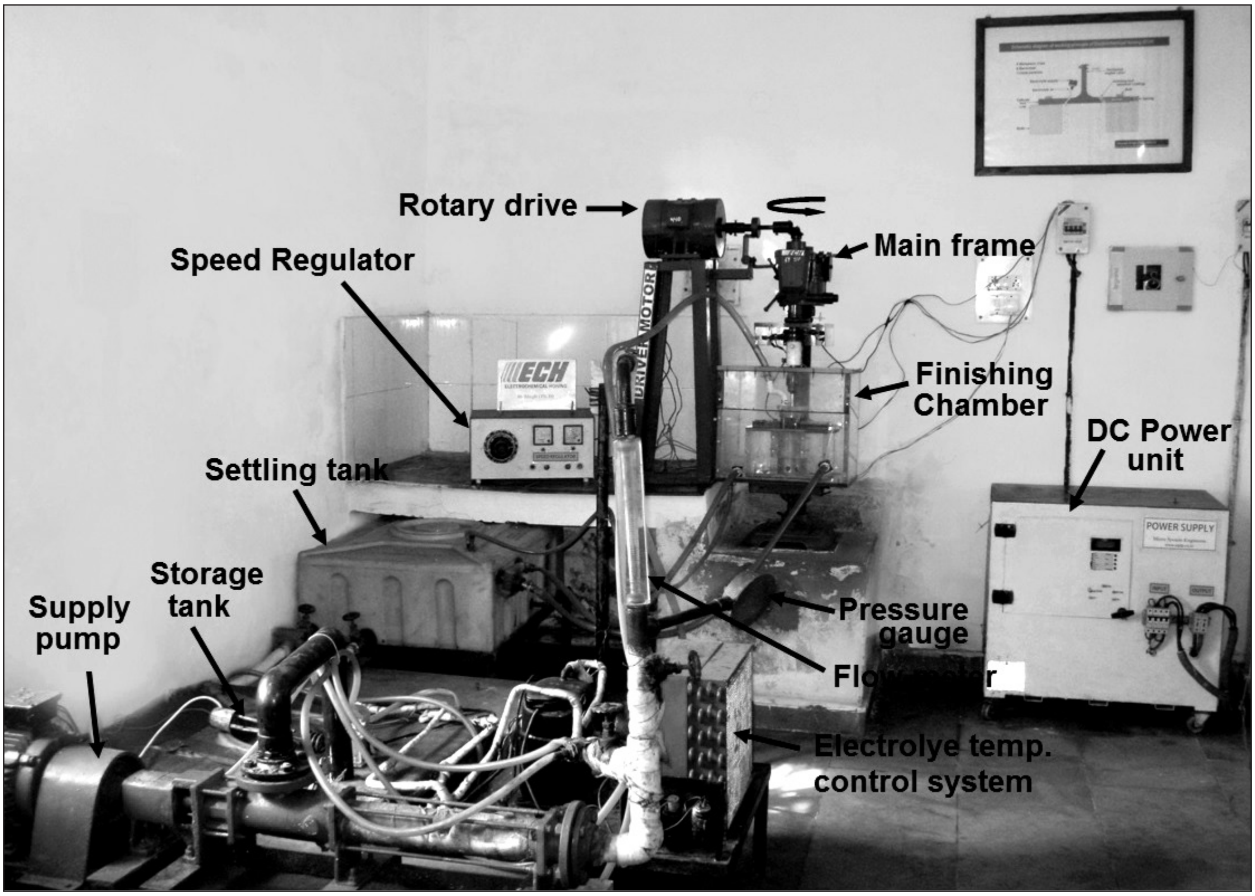

Fig 2. A Photographic View of the Developed Experimental Set up of Engine Valve Face

and the concentration has been discussed in this section. This section summarized the case study-I and case study-II, in which EN52 engine valve face and Ti6Al4V tuned shafts take as a workpiece respectively. The detail of the other process parameters are kept on their optimal level [8-11].

Roughness parameters (average surface roughness (R_a) and maximum surface roughness (R_t)) of the workpiece surface were evaluated before and after the process. The values of roughness parameters were measured using a Wyko NT 1100 optical profilometer interfaced with Vision®32 software. The percentage improvement in average surface roughness (PIRa) and percentage improvement in maximum surface roughness (PIRt) is calculated using the equation 1 and equation 2 respectively. Higher values of PIR_a/ PIR_t indicate the smaller value of final R_a/R_t. The percentage improvement in the out-of-roundness (PIOOR) is calculated using the equation 3.

$$PIR_a = \frac{Initial\ R_a value\ \text{-}\ Final\ R_a\ value}{Initial\ R_a} 100\% \quad \text{eq.1}$$

$$PIR_t = \frac{Initial\ R_t value\ \text{-}\ Final\ R_t\ value}{Initial\ R_t} 100\% \quad \text{eq.2}$$

$$PIOOR = \frac{Initial\ OOR\ value\ \text{-}\ Final\ OOR\ value}{Initial\ OOR} 100\% \quad \text{eq.3}$$

3.1 ECH of EN52 Engine Valve Face (Case Study-I)

The photographic view of the developed experimental set up is depict in Fig. 2. This setup has four subsystems namely (i) power supply system; (ii) electrolyte supply and recirculation system; (iii) finishing chamber housing workpiece, cathode and honing tools; and (iv) rotation system to the tooling system. Generally, copper is used as cathode; iron is used as anode and mixture of NaCl and $NaNO_3$ aqua solution in different ratio is used as electrolyte.

For the present study electrolyte composition and electrolyte concentration used as an input process variables to investigate the effect of

Table 1: List of Fixed Input Parameters of ECH of Engine Valve [7, 10]

Power	Voltage	Current		IEG	Processing time
	30 V	30 A		0.25 mm	3 minute
Electrolyte	Temperature			Flow	
	32^0 C			15 lpm	
Honing	Material	Rotary speed	Abrasive size	Honing pressure	Layer thickness
	NiCr	80 rpm	50-75 µm	2 MPa	100-150 µm
Tool	Tool box housing			Cathode tool material	
	Perspex and Bakelite			Copper	

Table 2: Chemical Composition of the Engine Valve Face Made of Material of EN52 Alloy Steel

Element	C	Cr	Mn	Si	S	P	Fe
Weight (%)	0.44	9.5	0.67	3.24	0.038	0.04	balanced

Table 3. Results of Experimentation of ECH of Workpiece Surface

Electrolyte Composition	PIR_a	PIR_t	PIOOR
100 % NaCl	63.34	69.31	46.74
90% NaCl + 10% $NaNO_3$	77.89	70.63	44.28
80% NaCl + 20% $NaNO_3$	79.60	74.26	51.01
70% NaCl + 30% $NaNO_3$	80.45	72.65	47.57
60% NaCl + 40% $NaNO_3$	73.04	72.89	36.45
Electrolyte Concentration	**PIR_a**	**PIR_t**	**PIOOR**
5 (% by Volume)	47.93	61.20	29.58
7.5 (% by Volume)	73.18	70.51	44.32
10 (% by Volume)	80.74	73.77	52.18

electrolyte (NaCl + $NaNO_3$) on the ECH of clad surfaces by analysing the surface roughness and morphology of finished surface before and after the process. The other input process parameters are fixed based on the literature review and the machine constraints as described in Table 1. The clad surface made of EN52 alloy steel is deposited on the engine valve face using HVOF thermal spray technique. The chemical composition of clad layer is presented in Table 2.

On the basis of the study, the results are illustrated in Table 3. Fig. 3(a) shows ratio of 70% NaCl, and 30% $NaNO_3$ gives higher PIR_a/PIR_t as compared to the other composition variations. The trend of composition variations can be explained as follow: The material removal rate in electrolyte dissolution depends on number of ions present in the solution as it determines the conductivity of the electrolyte solution. According to the molar concentration, pure NaCl has more number of ions in solution, but the addition of $NaNO_3$ in NaCl shows the accurate dissolution models, which helps to improve the surface quality uniformly. At the optimum setting of the electrolyte composition for ECH, the study of electrolyte concentration was presented in Fig.3(b). Results reveal that a higher percentage up to 10 increases the percentage improvement in surface roughness and MRR. The 10 % of the electrolyte composition in distilled water was selected as an optimum value.

3.2 ECH of Ti6Al4V Cylindrical Shafts (Case Study-II)

The photographic view of the developed experimental set up of ECH of cylindrical shafts Is shown in Fig. 4. To study the mixture of NaCl and $NaNO_3$ combination percentage in electrolyte, mixture D-optimal design is selected. As per design of experiment, nine experiments are conducted. The percentage by weight of NaCl is varied from 60 to 90% and of $NaNO_3$ from 10 to 40%. The statistical software used is "Design-Expert 6.0.7". The experimental runs are considered as a single block. The other input process parameters were fixed based on the literature review and the machine constraints as described in

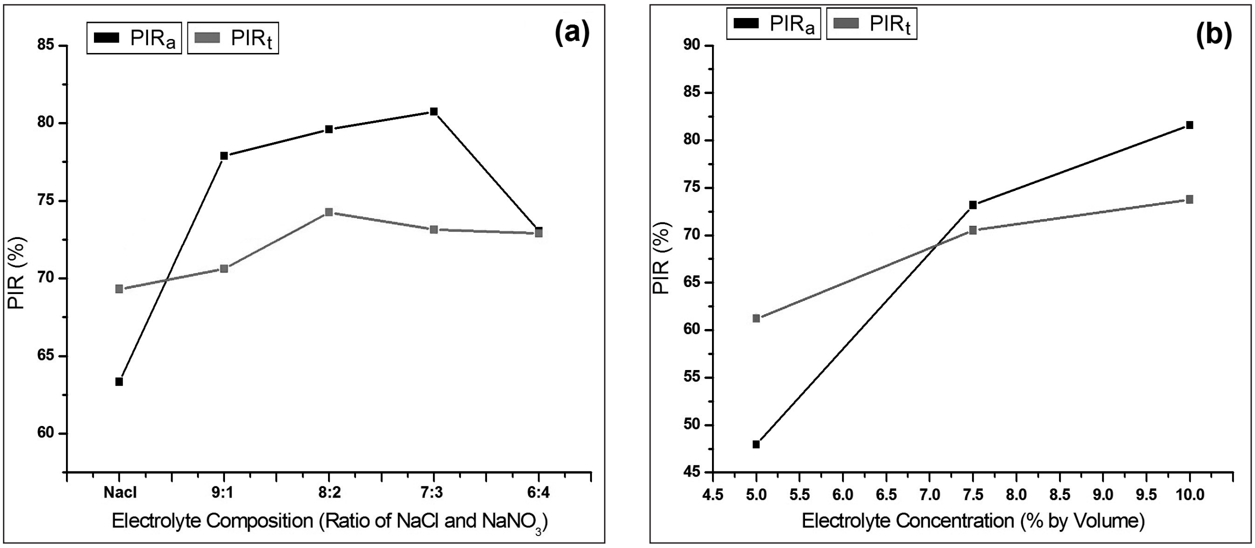

Fig 3. (a) Plot PIR_a/PIR_t - Electrolyte Composition; (b) Plot PIR_a/PIR_t - Electrolyte Concentration

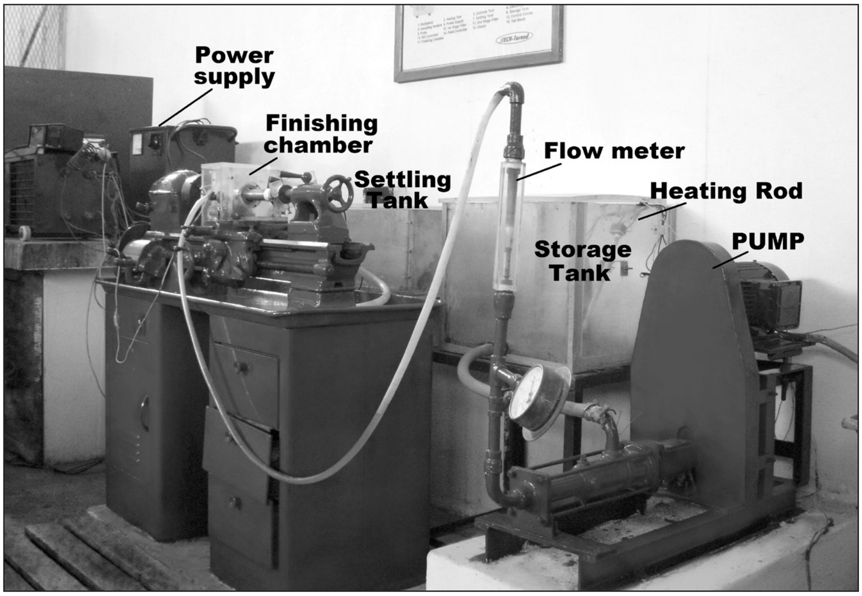

Fig 4. A Photographic View of the Developed Experimental Set Up of Cylindrical Shafts

Table 4: List of Fixed Input Parameters of ECH of Cylindrical Shafts [9, 11]

Power	Voltage	Current	IEG	Processing time
	15.2 V	22 A	0.5 mm	1.25 minute
Electrolyte	Temperature	Concentration		Flow
	30^0 C	10 %		4 lpm
Honing	Material	Axial feed rate	Grit size	Honing pressure
	SiC	11.43 mm/min	600	20 kPa
Tool	Tool box housing		Cathode tool material	
	Perspex and Bakelite		Copper	

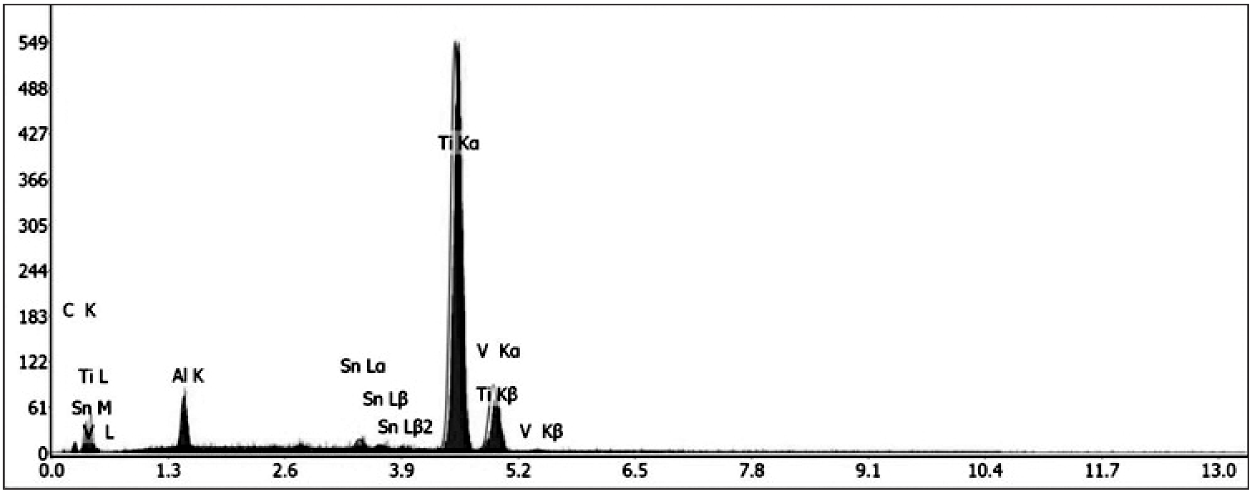

Fig. 5 Ti6Al4V Composition Data by EDX Analysis

Table 5: Values of the Input Parameters and the Responses for the Different Experiments

Run	NaCl %	$NaNO_3$ %	PIRa	PIRt	PIOOR
1	90	10	69.26	63.88	49.65
2	82.5	17.5	72.25	69.62	52.31
3	67.5	32.5	67.55	61.23	57.26
4	60	40	64.52	60.39	46.99
5	75	25	77.65	71.06	55.47
6	90	10	70.69	66.65	51.69
7	90	10	71.50	64.23	50.35
8	60	40	63.06	59.76	48.08
9	75	25	76.33	70.25	54.19

Table 4. The composition of Ti6Al4V alloy workpiece is obtained by EDX (Energy Dispersive X-ray) analysis as 6% aluminium, 4% vanadium and remaining % of titanium alloy as described in Fig. 5. Table 5 presents the values of variable input parameters and corresponding values of the three responses was for all the 9 experiments. Table 5 presents the results of ANOVA for percentage improvement in average roughness, maximum roughness, and out-of-roundness.

It is observed from Fig. 6 that the surface roughness improve with the addition of $NaNO_3$ in the NaCl solution from the start. On the other hand, out-of-roundness is initially fall down for a short period, after that it also start increasing. Beyond 23 percent content of $NaNO_3$, the trend of PIRa/PIRt certainly start fall down. The improvement in the out-of-roundness is remain increasing with the increases content of $NaNO_3$ up to 30 percent. Through the results analysis, it is justified that the identified optimum parametric combination is 77.18:22.82 for NaCl:$NaNO_3$ electrolyte, for precision finishing of Ti6Al4V cylindrical shafts using ECH process.

4. EFFECT OF NaCl AND KBr ELECTROLYTE

The effect of NaCl and KBr electrolyte combination under the various compositions and the concentration has been discussed in this section (Case study-III). In this study, Ti6Al4V cylindrical shafts take as a workpiece. To study the mixture of NaCl and KBr percentage in electrolyte, mixture D-optimal design is used. As per design of experiment, nine experiments are conducted. The percentage by weight of NaCl is varied from 60 to 90% and of KBr from 10 to 40%. The other input process parameters were fixed based on the literature review and the machine constraints as described in Table 4. Table 7 presents the values of variable input parameters and corresponding values of the three responses was for all the 9 experiments. Table 8 presents the results of ANOVA for percentage improvement in average roughness, maximum roughness, and out-of-roundness.

It is clear from the trend of PIRa, PIRt and PIOOR, the surface roughness and geometrical accuracy, improve with the addition of KBr in the NaCl solution initially. After a short period improvement in roughness parameters start decreasing with the increasing content of KBr. It is justified that the identified optimum parametric combination is 80.51:19.49 for NaCl:KBr electrolyte, for precision finishing of Ti6Al4V cylindrical shafts using ECH process.

Table 6: Results of ANOVA for Percentage Improvement in Average Roughness, Maximum Roughness, and Out-of-Roundness

Source	Sum of squares	Degree of freedom	Mean square	F-ratio	p-value Prob>F	Significant or insignificant at 95 % C.I.
(A) For percentage improvement in average surface roughness (PIRa)						
Model	149.25	2	74.62	16.45	0.0037	Significant
Linear mixture	47.62	1	47.62	10.50	0.0177	
AB	101.63	1	101.63	22.41	0.0037	
Residual	27.21	6	4.54			
Lack of Fit	23.52	2	11.76	12.75	0.0184	
Pure error	3.69	4	0.92			
Cor total	176.46	8				
(B) For percentage improvement in maximum surface roughness (PIRt)						
Model	85.61	3	28.54	25.93	0.0018	Significant
Linear mixture	38.82	1	38.82	35.27	0.0019	
AB	28.85	1	28.85	26.21	0.0037	
Residual	5.50	5	1.10			
Lack of Fit	0.046	1	0.046	0.034	0.8636	Not significant
Pure error	5.46	4	1.36			
Cor total	91.12	8				
(C) For percentage improvement in out-of-roundness (PIOOR)						
Model	86.93	3	28.98	24.02	0.0021	Significant
Linear mixture	1.04	1	1.04	0.86	0.3955	
AB	69.88	1	69.88	57.94	0.0006	
Residual	6.03	5	1.21			
Lack of Fit	2.47	1	2.47	2.77	0.1713	Not significant
Pure error	3.56	4	0.89			
Cor total	92.96	8				

5. STUDY ON SURFACE TOPOGRAPHY

The workpiece surface topography aspects such as a 3D plot of workpiece surface using optical profilometer and microstructure examination before and after the ECH has been done for all the three case studies. The following finding was identified by comparing the results of case studies.

(a) It is observed from the Fig. 8(a-b) of a case study-I, the surface texture of the finished surface through ECH, appears uniform, glazed and smooth. The height of asperities after finishing seem uniform in fashion. Before finishing, surface contains feed marks, scratches, voids, etc., which are significantly removed after ECH.

(b) As a compassion of the electrolytes for Ti6Al4V cylindrical shafts (case study-II and case

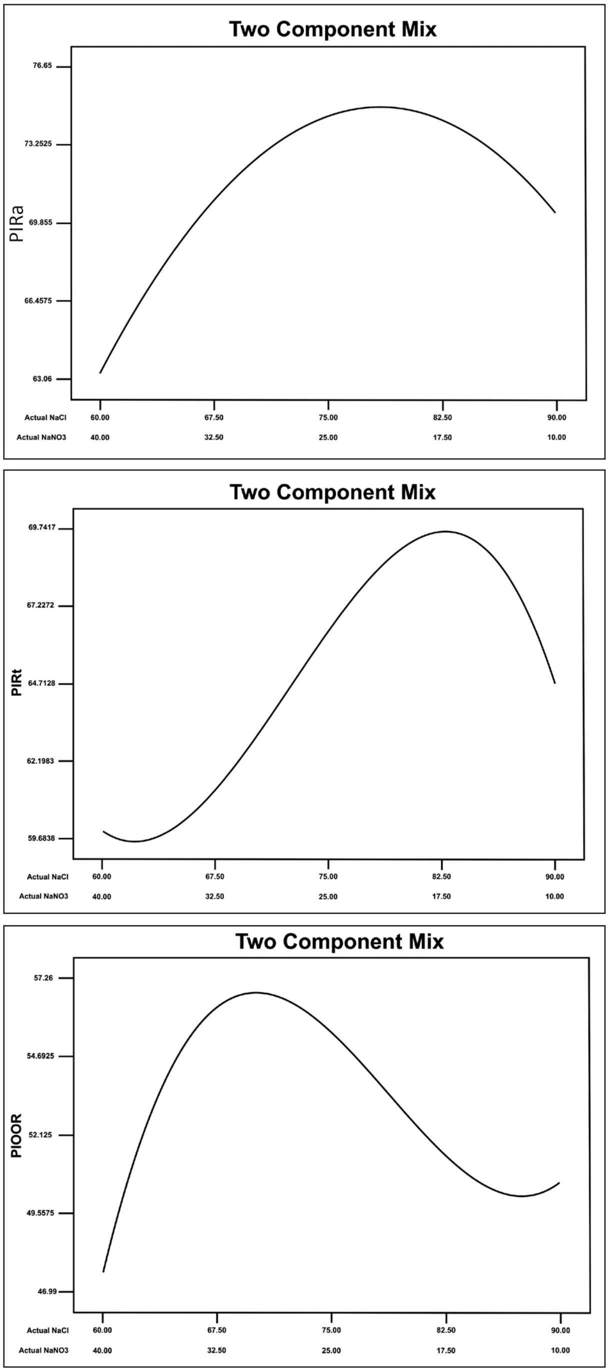

Fig 6. Variation of Percentage Improvements in Average Roughness (PIRa), in Maximum Roughness (PIRt), and in out-of-roundness (PIOOR) with Variation of Electrolyte Compositions

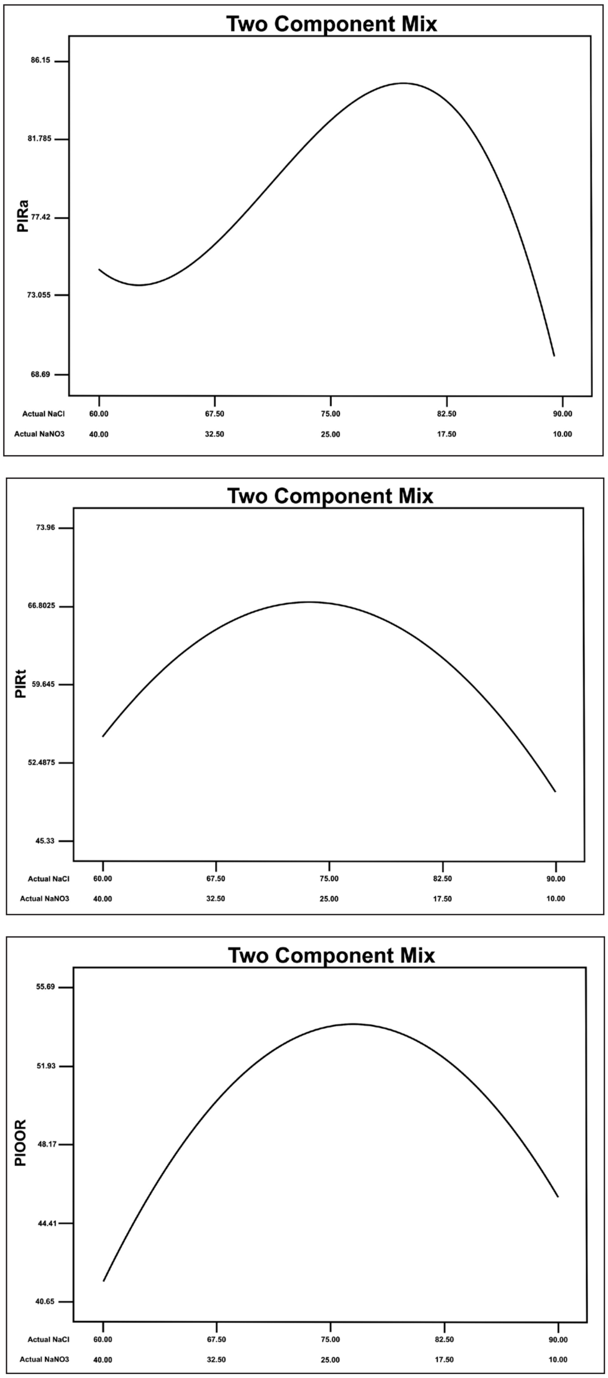

Fig 7. Variation of Percentage Improvements in Average Roughness (PIRa), in Maximum Roughness (PIRt), and in out-of-roundness (PIOOR) with Variation of Electrolyte Compositions

study-III), it is observed that the combination of NaCl with $NaNO_3$ gives better result as compared with the combination of NaCl with KBr in terms of aesthetic appearance and electrochemical reactions. Fig.9(a) shows that the ECH of Ti6Al4V shafts using NaCl and KBr electrolyte combination gives a purple colour and tiny voids are appearing on the surface topography. On the other side, ECH of Ti6Al4V shafts using NaCl and $NaNO_3$ electrolyte combination gives a uniform glazed surface as described in Fig. 9(b).

(c) The improvement in the surface roughness using NaCl and KBr electrolyte combination offered better result as compared to NaCl

Table 7: Values of the Input Parameters and the Responses for the Different Experiments

Run	NaCl %	KBr %	PIRa	PIRt	PIOOR
1	90	10	70.98	52.55	45.19
2	82.5	17.5	80.69	63.44	55.69
3	67.5	32.5	72.31	56.09	52.69
4	60	40	73.06	54.36	40.65
5	75	25	84.47	73.96	51.47
6	90	10	68.69	45.33	43.25
7	90	10	70.38	49.31	47.82
8	60	40	77.01	58.67	42.05
9	75	25	86.15	65.00	51.82

Table 8: Results of ANOVA for Percentage Improvement in Average Roughness, Maximum Roughness, and out-of-roundness

Source	Sum of squares	Degree of freedom	Mean square	F-ratio	p-value Prob>F	Significant or insignificant at 95 % C.I.
(A) For percentage improvement in average surface roughness (PIRa)						
Model	278.54	3	92.85	8.98	0.0186	Significant
Linear mixture	25.84	1	25.84	2.50	0.0174	
AB	191.12	1	191.12	18.48	0.0077	
Residual	51.71	5	10.34			
Lack of Fit	39.68	1	39.68	13.19	0.0221	
Pure error	12.03	4	3.01			
Cor total	330.25	8				
(B) For percentage improvement in maximum surface roughness (PIRt)						
Model	85.61	3	28.54	25.93	0.0018	Significant
Linear mixture	38.82	1	38.82	35.27	0.0019	
AB	28.85	1	28.85	26.21	0.0037	
Residual	5.50	5	1.10			
Lack of Fit	0.046	1	0.046	0.034	0.8636	Not significant
Pure error	5.46	4	1.36			
Cor total	91.12	8				
(C) For percentage improvement in out-of-roundness (PIOOR)						
Model	86.93	3	28.98	24.02	0.0021	Significant
Linear mixture	1.04	1	1.04	0.86	0.3955	
AB	69.88	1	69.88	57.94	0.0006	
Residual	6.03	5	1.21			
Lack of Fit	2.47	1	2.47	2.77	0.1713	Not significant
Pure error	3.56	4	0.89			
Cor total	92.96	8				

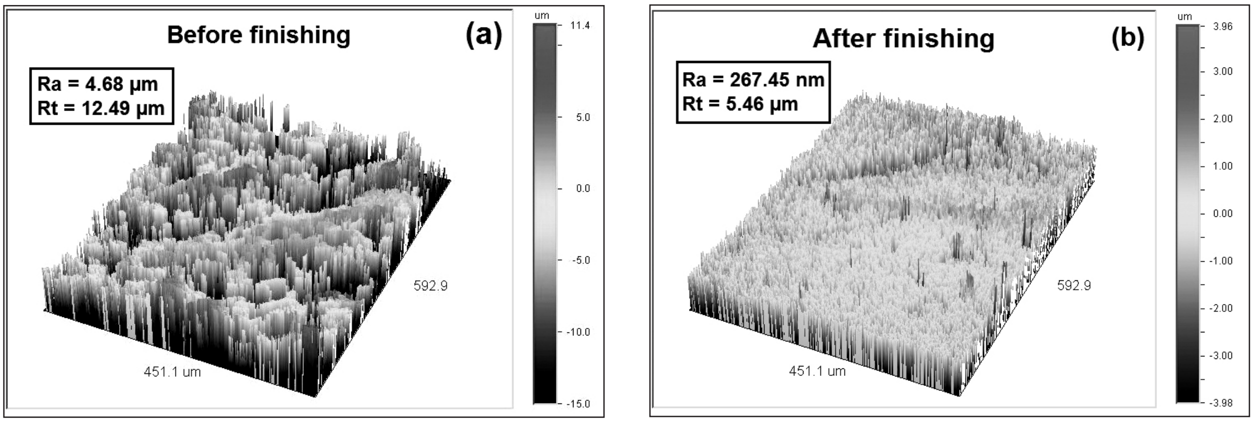

Fig 8. Topography of the Machined Surfaces Obtained Through Optical Profilometer: (a)Before Finished, (b)After Finishing

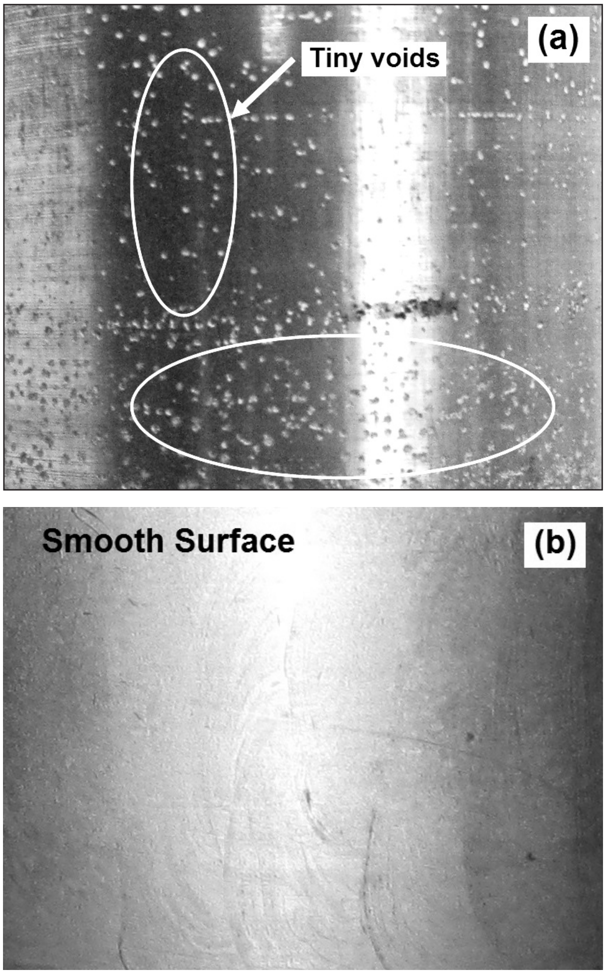

Fig 9. Surface Appearance Using Microscope: (a) NaCl and KBr Electrolyte, (b) NaCl and $NaNO_3$ Electrolyte

and $NaNO_3$ electrolyte combination. But, due to the high reactivity at 32^{0}C temperature of NaCl and KBr electrolyte combination, which will ultimately increase the corrosion protections and maintenance cost.

6. CONCLUSIONS

In the present work, different combinations of electrolytes were considered for the experimentation and to determine their influence on surface integrity in the electrochemical honing process. The experimentation was carried out by varying chemical composition in combination (NaCl and $NaNO_3$ or NaCl and KBr) as per mixture D-optimal design approach. On the basis of the results, main conclusion can be stated as the selection of appropriate electrolyte combinations and their composition is crucial to achieve the efficiency and high quality of outcome from the ECH process. It is found that the NaCl and $NaNO_3$ electrolyte combination gives defect free surface finishing for TI6Al4V cylindrical shafts as compared to NaCl and KBr. Furthermore, similar experiment results were obtained during finishing of EN52 clad surfaces of engine valve faying face using NaCl and $NaNO_3$ electrolyte combination.

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"3D printing has digitized the entire manufacturing process"
- Peter Diamandis

"Nanotechnology is manufacturing with atoms"
- William Powell