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Optimization of Processing Parameters in Electrochemical Machining of AISI 304 using Taguchi Design Technique

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Abstract— Electro chemical polishing is a process by which metal is removed from a work piece by passage of electric current while the work is submerged in a specially-designed solution. This study investigate the effect of temperature, current, time and electrolyte composition on the surface characteristics and metal removal rate (M.R.R.) of austenitic stainless steel AISI 304 in phosphoric acid and sulphuric acid bath. In case of MRR, time was the most influential factor and then the relative influence decreases in the order current (I), temperature (T) and electrolyte composition (C). For Surface Roughness it was seen that temperature (T) being the most influential factor and current (I), electrolyte concentration(C) and time being less influential in the order they are mentioned.

Index Terms—AISI 304, Electrochemical machining, Optimization

I. INTRODUCTION

Electrochemical Machining (ECM) is a nonconventional machining process used mainly to cut hard or difficult to cut metals, where the application of a more traditional process is not convenient. It offers several special advantages including higher machining rate, better precision and control, and a wider range of materials that can be machined. Kao and Hocheng, (2003) reported grey relational analysis useful for the multi-input discrete data and uncertain experimental study, the application of grey relational analysis for optimizing the electro polishing of 316lL SS with multiple performance characteristics. As a result, the target performance characteristics (surface roughness and passivation strength) improved through this method. Electrolyte used was a compound of phosphoric acid, sulphuric acid, glycerin and water. K.A. Padmanabhan et al., (1995) found improvement in low-cycle fatigue (LCF) life by a superior surface finish, and the effect was more pronounced in the low strain amplitude region. The LCF life could be increased by about 87% at strain amplitude of 0.40% by electro polishing a sample compared with polishing it with a 100 emery drill paper. Hu et al., (2003) have successfully completed electro-polishing on cemented carbide. The uniform distribution of the original structure and gas holes were observedbythem, while those before electro polishing have a gap, thick gains and piled-up material. The main components of the electrolyte were NaOHNa2SiO3- DTPA. N. Unlu et al., (2007) used double-jet electro polishing technique for the preparation of high quality Al TEM specimen. He found that the parameters such as voltage, current density, temperature, time, and electrolyte have significant importance in surface finish of the specimen.

However, Ramaswamy, (2002) used four different electrolytes in an ECP to access the effect on the surface topography of EDM surfaces. The acidic medium has better polishing effect on the surface topography of the component. The surface exposed by the ECP action in the case of the acid electrolyte is smoother and more reflective than those of the salts. The relationship between the electropolishing rate and time follows a near sigmoidal law. E.-S. Lee,(2000) The aim of this study is to determine characteristics of electropolishing stainless steel tubes (STS316L) in terms of current density, machining time, temperature, electrode gap and work-piece surface roughness. The various parameters used were Electrolyte:-H_3PO_4 +$H2SO_4$
Cathode:-Cu (Φ6, 5, 4, 3 mm)
Time:-2min
Electrode gap 0.5-2.0mm
Temp 20-900c
The surface roughness improves as polishing time increases. As electrolyte temperature raises the electro polishing effect becomes more active with high current efficiencies caused by low viscosity and continuous supply of fresh electrolyte. Higher corrosion can be achieved due to passivation effect. This paper attempts to optimize the predominated machining parameters in Electro Chemical Machining (ECM) of AISI 304 using Taguchi L 18 orthogonal array design of experiment.

II. EXPERIMENTAL DETAILS

2.1 Material-

Austenitic stainless steels are widely used in aircraft industries, architectural purposes, chemical processing and food processing industries, household items, dairy industries, textile industries, transportation industries, furnace parts, machine parts, spun parts chemical and photographic processing, chemical processing equipments. Austenitic S.S. 304 is available in the form of sheets, annealed strips, cold finished high tensile bars. It has tensile strength - 517 MPa, yield strength - 207 MPa , % elongation - 40 and hardness 92 RB. Composition of austenitic stainless steel is shown in table 1

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Table 1: Composition of AISI 304 S.S.

Element	Cr	Ni	C	Mn	P	Si	S
% Amount	18-20	8-10.5	0.08-0.8	2	0.045	1	0.03

Austenitic stainless steel is non magnetic and has wide range of applications. The Ø6mm x 20mm test specimens were sheared from Ø6mm x 300mm AISI 304 S.S. rod. Three different concentrations of phosphoric acid and sulphuric acid were used in the experiment: 70:30, 60:40, and 50:50% (v/v). Each concentration was obtained by adding a set amount of H2SO4 and H3PO4 acid to obtain the desired acid concentration.

2.2 Experimental Setup-

1. Surface preparation of AISI 304 S.S. alloy specimen for electro chemical polishing.
2. I-V curve generation by varying time, temperature, and acid concentration to determine current.
3. Electro chemical polishing, with temperature, time, and current as variables.
4. Surface roughness analysis of each test specimen and calculation of rate of electro chemical polishing. Electro chemical polishing was conducted in a 1L Glass beaker, Stainless steel cylinder 60mm diameter with one end closed was used as the cathode, the apparatus and the equipment used for electro chemical polishing are shown in Fig. 9.

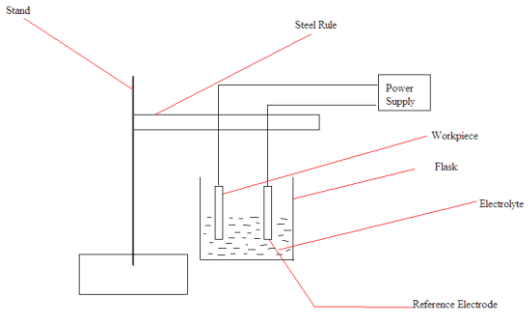

Fig. 1: A simplified circuit diagram Electro chemical polishing Setup

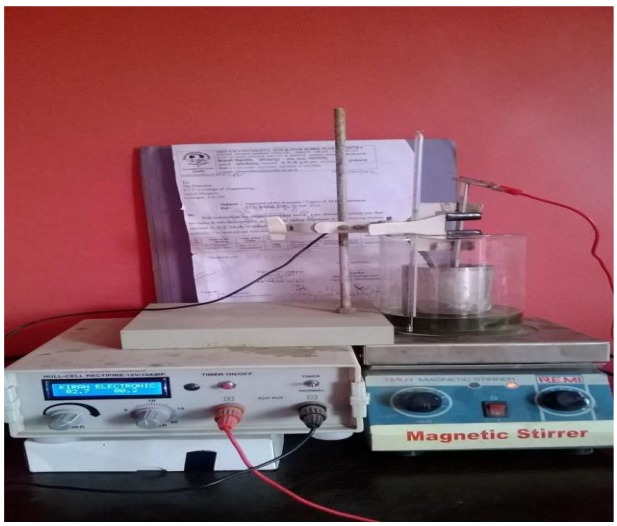

Fig. 2: Electro chemical polishing apparatus and equipments.

2.3 Specimen Preparation-

Test specimens were cleaned in accordance with ASTM B322-99. The specimen edges were deburred by mechanically polishing for 5 second at a constant force with 300 grit SiC paper. The test specimens were then mechanically polished for 1 min. at constant force with 300 grit SiC paper, with DI water as the lubricant and coolant, in order to establish a standard start surface roughness. The specimens were then cleaned by sonication in a 70% IPA bath for 5 min., followed by sonication in DI water for an additional 5 min. before air drying. Post-cleaning was conducted by following the procedures specified in ASTM B912-02. After electro chemical polishing, test specimens were dipped in 100 ml DI water to remove the acid and the test specimens were sonicated in 100 ml DI water for 3 min. to remove any residual acid and surface contaminants. The specimens were then air dried.

Table 2: Electro chemical polishing parameters used to generate the I-V curve

Machining Parameters	Symbol	Unit	Level		
			Level-1	Level-2	Level-3
Temp.erature	T	Degree centigrade	50	70	80
Acid Composition	C	% (v/v)	50:50	60:40	70:30
EP time	Time	Minute	5	10	15

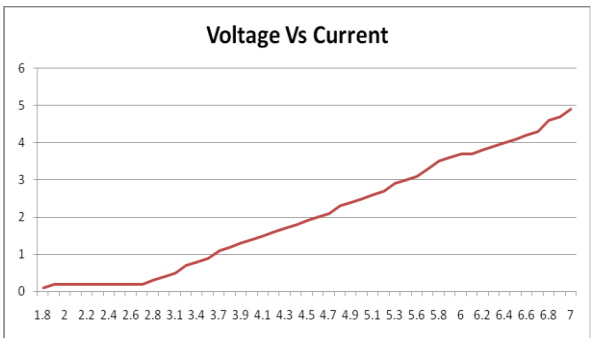

Fig. 3: I-V Curve for Acid composition 50:50, Temp-500C, TIME-5 min

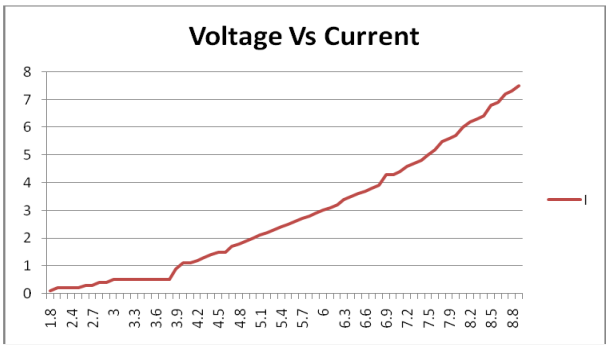

Fig. 4: I-V Curve for Acid composition 60:40, Temp.-800C, TIME-5 min

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Fig. 3 and 4 depict that at 0.2 and 0.5 Amp current is constant hence selected as current parameters for electro polishing. As a temperature decreases from 800c to500c there is formation of decreased current plateau of 0.2A over wide voltage range.

Table 3 Control and fixed parameters utilized to characterize the surface characteristics.

Machining Parameters	Symbol	Unit	Level		
			Level-1	Level-2	Level-3
Temperature	T	Degree centigrade	50	70	80
Acid Composition	C	Milliliter	50:50	60:40	70:30
EP time	Time	Minute	3	5	10
Current	I	Ampere	0.2	0.5	--

Fixed Parameters Cathode: - S.S. Cylinder Anode: - AISI 304 S.S. Rod Electrode Distance: - 30 mm

III. RESULTS AND DISCUSSION

The response table for MRR and Roughness are shown in Table 4

Table 4: Response table

Expt. No.	Current (Amp)	Temp. (°c)	Electrolyte conc. (H_3PO_4:H_2SO_4)	Time (min)	Wt. Loss (gm)	MRR (gm/cm2 min)	Roughness, Ra(µm)
1	0.2	50	50/50	5	0.03	1.06 X 10-04	0.435
2	0.2	50	60/40	10	0.02	3.53 x 10-05	0.457
3	0.2	50	70/30	15	0.03	3.53x 10-05	0.6
4	0.2	70	50/50	5	0.02	8.84 x 10-05	0.487
5	0.2	70	60/40	10	0.02	3.53 x 10-05	0.648
6	0.2	70	70/30	15	0.03	3.53 x 10-05	0.633
7	0.2	80	50/50	10	0.04	7.07 x 10-05	0.681
8	0.2	80	60/40	15	0.04	4.71 x 10-05	0.416
9	0.2	80	70/30	5	0.04	1.06 x 10-04	0.482
10	0.5	50	50/50	15	0.05	6.48 x 10-05	0.478
11	0.5	50	60/40	5	0.03	1.06 x 10-04	0.548
12	0.5	50	70/30	10	0.04	7.07 x 10-05	0.350
13	0.5	70	50/50	10	0.05	8.84 x 10-05	0.758
14	0.5	70	60/40	15	0.07	5.89 x 10-05	0.495
15	0.5	70	70/30	5	0.02	1.41x 10-05	0.771
16	0.5	80	50/50	15	0.09	1.06 x 10-04	0.888
17	0.5	80	60/40	5	0.02	1.41 x 10-04	0.964
18	0.5	80	70/30	10	0.04	7.95 x 10-05	0.536

Table 5: Analysis of Variance for S/N ratios for MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I	1	81.618	81.618	81.618	110.58	0.000
Time	2	148.551	148.551	74.276	100.63	0.000
T	2	26.372	26.372	13.186	17.87	0.000
C	2	27.154	27.154	13.577	18.4	0.000
Error	10	7.381	7.381	0.738		
Total	17	291.076				

Table 6: Response Table for S/N Rations Larger is better (MRR)

Level	I	T	C	Time
1	-85.08	-83.97	-81.31	-78.92
2	-80.82	-83.63	-84.27	-84.52
3		-81.25	-83.25	-85.4
Delta	4.26	2.72	2.96	6.49
Rank	2	4	3	1

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The MRR was found directly proportional to current in the range of 0.2 to 0.5A. The graph clearly depicts increase in MRR with increase in current density. This is because at the beginning raise in the current density speeds up the smoothing process. As the current density increases, the time of treatment is reduced to the balance between film growing and film depletion.

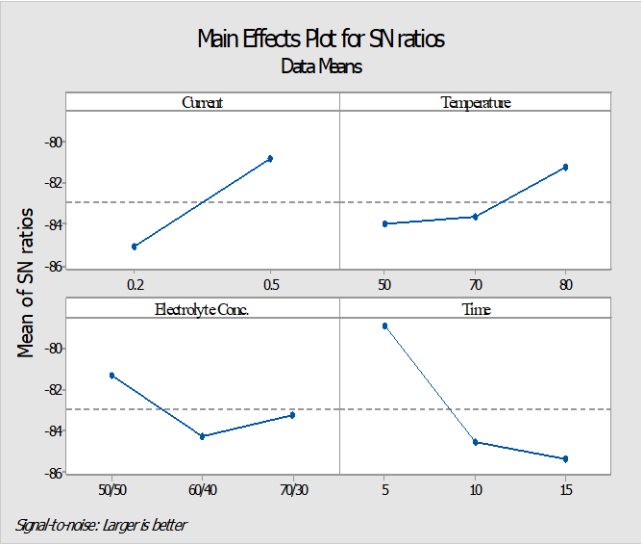

Fig. 5: Main effect plot for S/N ratios (MRR)

The fig. 5 also depicts the incremental trend of the MRR with temperature. This is due to the raise in temperature of the solution favours the formation of passive film on the surface of anode. At the same time as a result of increase the rate of diffusion of the acid, the rate of dissolution of the film also increase. As passive film is formed rapidly, resistance increases. This will cause removal of material from the peaks at micro level. At lower temperature, polishing rate slow and uneconomical.

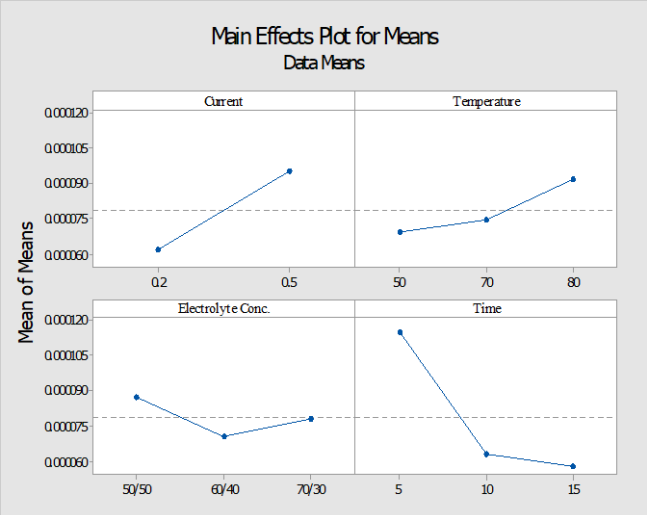

Fig. 6: Main Effects Plot for Means (MRR)

3.1 Model Analysis of MRR

Table 7: Estimated Model Coefficients for SN ratios

Term	Coef	SE Coef	T	P
Constant	-82.9470	0.2025	-409.627	0.000
I 0.2	-2.1294	0.2025	-10.516	0.000
T 50	-1.0191	0.2864	-3.559	0.005
T 70	-0.6815	0.2864	-2.380	0.039
C 50/50	1.6338	0.2864	5.705	0.000
C 60/40	-1.3276	0.2864	-4.636	0.001
Time 5	4.0306	0.2864	14.075	0.000
Time 10	-1.5736	0.2864	-5.495	0.000
S = 0.8591	R-Sq = 97.5%		R-Sq(adj) = 95.7%	

adjusted R2 (=95.7 %.) may get smaller. The standard deviation of errors in the modeling, S= 0.8591 .Comparing the p-value to a commonly used α-level = 0.05, it is found that if the p-value is less than or equal to α, it can be concluded that the effect is significant (shown in bold), otherwise it is not significant.

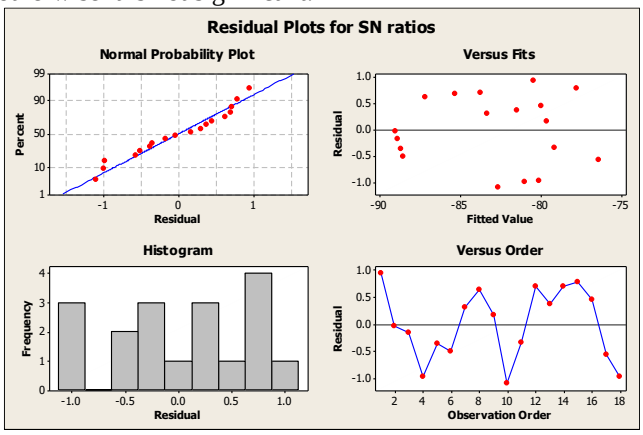

Fig. 7: Residual plot for MRR

The residual plot of MRR is shown in fig. 7. This layout is useful to determine whether the model meets the assumptions of the analysis. The residual plots in the graph and the interpretation of each residual plot indicate below:

a. Normal probability plot indicates the data are normally distributed and the variables are influencing the response. Outliers don't exist in the data, because standardized residues are between -1 and 1.

b. Residuals versus fitted values indicate the variance is constant and a non linear relationship exists as well as no outliers exist in the data.

c. Histogram proves the data are not skewed and not outliers exist.

d. Residuals versus order of the data indicate that there are systematic effects in the data due to time or data collection order.

3.2 Empirical Modeling for M.R.R.

With the help of data obtained through experimentation, regression analysis was carried out and following correlations was obtained for material removal rate:

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(For Electrolyte composition 50/50)
MRR= 0.000061 + 0.000110 Current + 0.000001 Temperature - 0.000006 TIME
(For Electrolyte composition 60/40)
MRR = 0.000045 + 0.000110 Current + 0.000001 Temperature - 0.000006 TIME
(For Electrolyte composition 70/30)
MRR = 0.000052 + 0.000110 Current + 0.000001 Temperature - 0.000006 TIME

3.3 Influences on Surface Roughness

The S/N ratios for Surface Roughness are calculated as given in Equation 1. Taguchi method was used to analyze the result of response of machining parameter for smaller is better (SB) criteria.

$$SB{:}\eta = -10\log[\tfrac{1}{n}\textstyle\sum_{i=1}^{n} yi^2] \quad \text{....(1)}$$

Table 8: Analysis of Variance for SNRA3, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I	1	7.294	7.294	7.294	1.19	0.302
T	2	24.415	24.415	12.208	1.98	0.188
C	2	2.041	2.041	1.021	0.17	0.849
Time	2	0.882	0.882	0.441	0.07	0.931
Error	10	61.551	61.551	6.155		
Total	17	96.183				

The analysis of variances for the factors is shown in Table 8 which clearly indicates that the current (I), time, temperature (T) and electrolyte composition(C) are not the influencing factors for surface roughness.

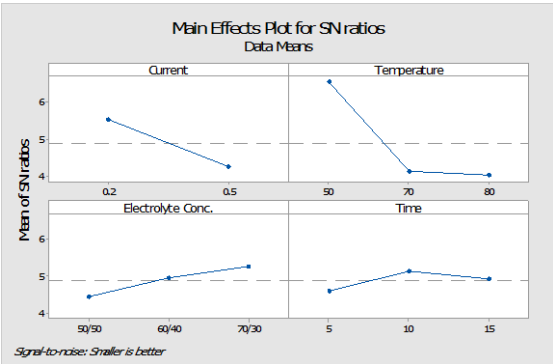

Fig. 8: Main effect plot for S/N ratios (Surface Roughness)

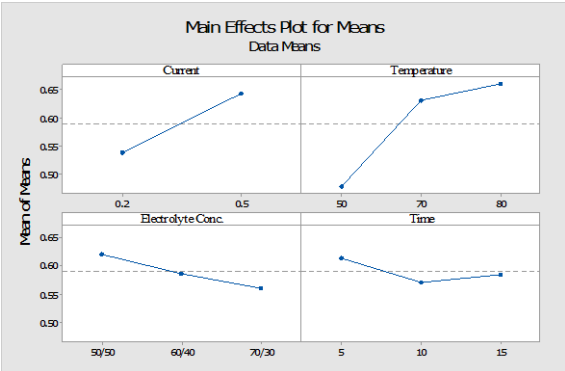

Fig. 9: Main effect plot for Means (Surface Roughness)

From fig. 8 as EP time increased, the surface roughness decreased. The surface roughness decreased with an increase in the EP time until 10 min. At a longer duration of electro chemical polishing at EP time of 15 min., the surface roughness increased and pits formed. The surface roughness decreases as the bath temperature decreases from 800c to 50°C, while maintaining a constant EP time. The current study revealed that as the process current increases, the surface roughness increases as shown in fig. 9. The surface roughness increases as electrolytic composition decrease from 70/30 to 50/50 as shown in fig. 6.

Table 9: Response Table for Signal to Noise Ratios Smaller is better

Level	I	T	C	Time
1	5.528	6.537	4.444	4.603
2	4.255	4.127	4.973	5.142
3		4.010	5.257	4.930
Delta	1.273	2.527	0.813	0.538
Rank	2	1	3	4

The delta values are time (T), electrolyte composition (C), current (I), temperature (T) are 0.538, 0.813, 1.273and 2.527respectively, in Table 8. The case of Surface Roughness Smaller is better, so from this table it is clearly definite that temperature (T) is the most important factor then current(I), electrolyte composition(C), and last is time (Time).

3.4 Model Analysis of Surface Roughness

The coefficients of model for S/N ratios for surface roughness are shown in Table 10. The parameter R2describes the amount of variation observed in surface roughness is explained by the input factors. R2= 36 % indicate that the model is able to predict the response with high accuracy. Adjusted R2is a modified R2that has been adjusted for the number of terms in the model. If unnecessary terms are included in the model, R2can be artificially high, but adjusted R2(=0.0 %.) may get smaller. The standard deviation of errors in the modeling, S= 2.481.

Table 10: Estimated Model Coefficients for SN ratios

Term	Coef	SE Coef	T	P
Constant	4.89154	0.5848	8.365	0.000
I 0.2	0.63656	0.5848	1.089	0.302
T 50	1.64568	0.8270	1.990	0.075
T 70	-0.76433	0.8270	-0.924	0.377
C 50/50	-0.44713	0.8270	-0.541	0.601
C 60/40	0.08163	0.8270	0.099	0.923
Time 5	-0.28813	0.8270	-0.348	0.735
S = 2.481 R-Sq = 36.0% R-Sq(adj) = 0.0%				

The residual plot of MRR is shown in Fig 10. This layout is useful to determine whether the model meets the assumptions of the analysis. The residual plots in the graph and the interpretation of each residual plot indicate below:

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a. Normal probability plot indicates the data are normally distributed and the variables are influencing the response. Outliers don't exist in the data, because standardized residues are between -2.5 and 2.5.
b. Residuals versus fitted values indicate the variance is constant and a nonlinear relationship exists as well as no outliers exist in the data.
c. Histogram proves the data are not skewed and not outliers exist.
d. Residuals versus order of the data indicate that there are systematic effects in the data due to time or data collection order.

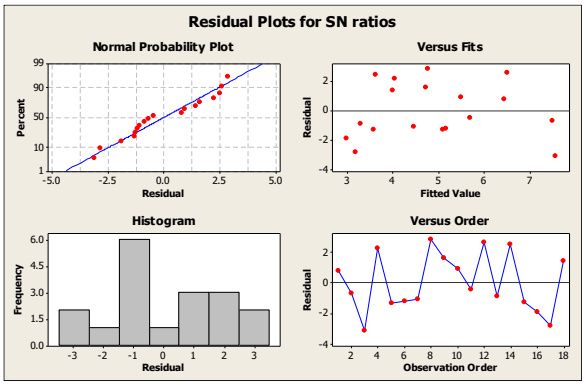

Fig. 10: Residual plot for Surface Roughness

3.5 Empirical Modelling for Surface Roughness

With the help of data obtained through experimentation, regression analysis was carried out and following correlations was obtained for Surface Roughness (SR).
(For electrolyte composition 50/50)
SR = 0.105 + 0.351 current + 0.00633 temperature - 0.00295 time
(For electrolyte composition 60/40)
SR = 0.072 + 0.351 current + 0.00633 temperature - 0.00295time
(For electrolyte composition 70/30)
SR = 0.046 + 0.351 current + 0.00633 temperature - 0.00295 time

Table 11: The optimum parameter

Physical require ment	Optimal combinations					
	Curre nt (A)	Tem pera ture (0C)	Ti me (mi n)	Electrol yte compos ition	Predi cted value	% of Pred icted erro r
Maximu m MRR	0.5	80	5	50/50	0.000 153	08
Minimu m Surface Roughne ss	0.2	50	10	70/30	0.378	04

IV. CONCLUSION

The machining parameters for electrochemical machining of AISI 304 composites are optimized with L18 orthogonal array. From the investigation, the following conclusions can be drawn:

i) The wide current plateau on the I-V curve indicated a constant current was obtained at lower temperatures (500 C). Since polishing rate and current are correlated, by keeping the current constant it can allow for greater control over the electro polishing process. The presence of a current plateau was found to be dependent on the temperature of the acid bath.
ii) The surface roughness was mainly influenced by temperature (T), followed by current (I) and electrolyte composition(C) and time. As well as the surface roughness increases as electrolytic composition decrease from 70/30 to 50/50.
iii) The material removal rate was mainly influenced by time, followed by current (I), temperature (T) and electrolyte composition(C).
iv) The recommended levels of ECM machining parameters for maximizing metal removal rate are Current 0.5 A, Temperature 80 °C, Time 5 min. and Electrolyte composition 50/50
v) The recommended levels of ECM machining parameters for minimizing surface roughness are Current 0.2 A, Temperature 50° C, Time 10 min and Electrolyte composition 70/30.

FUTURE SCOPE

Surface integrity studies could be undertaken as future studies, using combination of EDM with electropolishing on some materials. Further study is necessary to investigate the performance in different ranges, and find the global optimum parameters. It is necessary to find out single optimal parameter setting to satisfy the requirement of excellent surface finish and MRR. Effect of electropolishing process on corrosion resistance and reflectivity are not done in this work, hence these studies could be considered as future scope.

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