COST- TOLERANCE PREDICTION MODELS FOR ELECTROCHEMICAL MACHINING OF METAL MATRIX COMPOSITES

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Abstract:

Electrochemical machining (ECM), is an advanced manufacturing technique capable of machining hard composite materials with good tolerance. However, the huge investment and operating costs make the ECM process uneconomical. This work is hence intended to develop cost-tolerance relationship for ECM process for 6061Al/10%wt Al_2O_3/5%wt SiC composites. The coefficient of determination (R^2) values justifies the adequacy of developed cost and tolerance models. Analysis of variance (ANOVA) test is performed to understand the effect of ECM process parameters on cost and tolerance. The process parameters such as current, voltage and feed rate significantly affect the operating costs while the tolerance is affected by all the parameters.

1 Introduction

In modern manufacturing area, there has been a rapid growth in development of the harder, tougher and stronger work piece materials which are very difficult and uneconomical to be machined with traditional machining techniques. Machining of such materials by using conventional machining methods will result in poor dimensional accuracy and surface finish. Electrochemical machining (ECM) as one of the non conventional machining processes, can solve the above difficulty with relative ease. Component tolerance is the most significant parameter in manufacturing since it affects the manufacturing cost of a product. Machining of metal matrix composites (MMCs) with a traditional machining process has its disadvantage of quick tool failure [1]. Producing good surface finish on the composite materials is a tough task with a conventional machining process. Several works were done in the direction to study the machinability issues of MMCs with different machining methods [2-4]. Taweel [5] studied the machining characteristics of Al/Al2O3 composite by using electrochemical turning (ECT) with magnetic abrasive finishing (MAF). Senthilkumar et al. [6] investigated the electrochemical machining characteristics of Al/SiCp composites by using response surface methodology. Machining suitability of Al/B4C composites with electrochemical machining was also investigated [7, 8]. The influence of reinforcement of SiC particles in aluminum matrix was investigated and other ECM process parameters were optimized by Senthilkumar et al. [9]. The abrasive nature of ceramic particles reinforced in the metallic matrix erodes the tool reducing thus the life time of the tool. ECM tool is not affected by wear because it is an electrochemical dissolution process. ECM can machine MMCs with reasonable surface finish and dimensional accuracy. But the investment and machining cost of the ECM process are high. If

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the relationship between the tolerance and the cost of producing that tolerance is known, a least-cost process sequence may be applied to machining MMCs. No work has been reported in the literature for the identification of cost-tolerance relationship for electrochemical machining of MMCs. In this competitive world, it is very important to utilize the full potential of ECM in order to meet the demands on tolerances and costs. Therefore, the present work is aimed at developing the cost tolerance prediction models for electrochemical machining of 6061Al/10%wt Al2O3/5%wt SiC composite.

2 Experimental works

ECM is a controlled anodic dissolution process at atomic level of the work piece that is electrically conductive by a shaped tool through an electrolyte as shown in Fig. 1. In ECM, the work piece is an anode and the tool is a cathode and the electrolyte is pumped through the gap between the tool and the work piece, while direct current is passed through the cell to dissolve metal from the work piece. Fig. 2 shows the experimental set-up of METATECH-ECM used in this work. The 6061Al/10%wt Al_2O_3/5%wt SiC composites were prepared through stir casting process. The composites were of diameter 40 mm and of height 10 mm. The tool used in the ECM is made up of copper with a circular cross section. The electrolyte used was aqueous solution of sodium chloride (NaCl). The electrolyte solution is fed to the work piece axially through a hole in the tool. Since sodium chloride solution has no passivating effect on the job surface, it was used as an electrolyte.

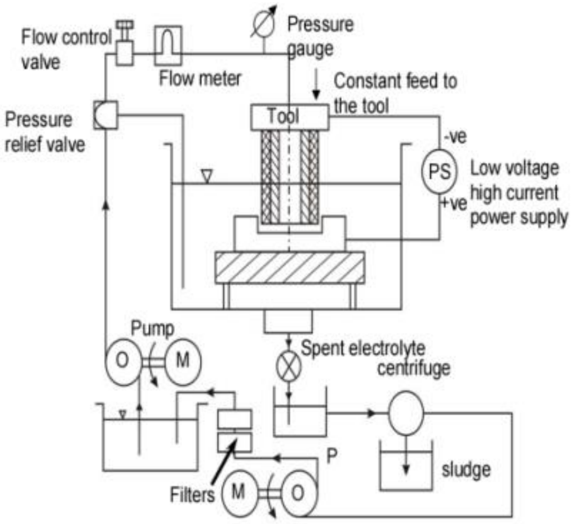

Figure 1. Principle of ECM.

Figure 2. Experimental set up of ECM: a) Total feed system, b) Control panel, c) Machinery chamber, d) Electrolyte tank.

Table 1. Process parameters and levels

Symbol	Parameter	Coded values	Level				
			-2	-1	0	1	2
U	Flow rate (l/min)	x_1	7	9	11	13	15
F	Feed rate (mm/min)	x_2	0.2	0.4	0.6	0.8	1
V	Voltage (V)	x_3	10	14	18	22	26
IEG	Inter-electrode gap (mm)	x_4	0.1	0.2	0.3	0.4	0.5
C	Current (A)	x_5	205	220	235	250	265
EC	Electrolyte concentration (g/l)	x_6	100	130	160	190	220

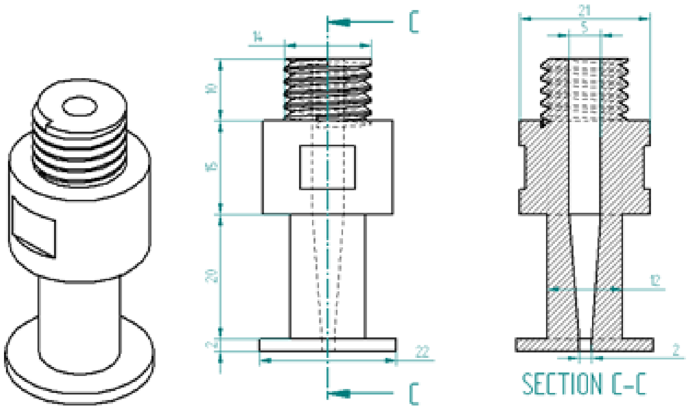

Figure 3. 3D model and cross sectional view of tool.

Fig. 3 shows the 3D model and cross sectional view of the tool. Box-Behnken design of response surface methodology (RSM) was used for designing and analyzing the experiments [12-13]. Fifty four tests were carried out with selected parameter combinations according to RSM. Higher current density of 110 A/cm^2 was used so as to have high material removal. The main process parameters governing the ECM process i.e. voltage (V) setting, inter-electrode gap (IEG), electrolyte concentration (EC), electrolyte flow rate (U), tool feed rate (F) and current (C) are considered in this work and their levels are shown in Table 1.

The coded values were obtained from the following equation:

$$x_i = \frac{Chosen\ \ values - Central\ value\ of\ parameters}{Interval\ of\ variation}, \qquad (1)$$

where, x_i is the coded values of the variables U, F, V, IEG, C and EC, respectively. The width of the specimen was measured through a profile projector. Tolerance of the machined specimens is calculated using the following relation:

$$\delta = \sqrt{\left(\frac{\sum(b_i - X)}{n-1}\right) * 6}, \qquad (2)$$

where

$$X = \frac{\sum b_i}{n}, \qquad (3)$$

b_i = average width of the specimen,
n = number of specimens in each parameter set.
The tolerance values are displayed in Table 2.

3 Machining cost evaluation

The following cost elements of electrochemical machining process are considered [10, 11].

3.1 Machine cost (*M*)

This component consists of the machine depreciation rate and the machine overhead. The depreciation rate is calculated based on 9 hours of machining time per day and the 240 productive days per year. The amortization period is 5 years. The machine overhead includes the cost of routine maintenance, the cost of unexpected breakdowns and services, and the cost of factory space used. This is estimated to be about 30% of the depreciation rate.

Equipment cost = \$ 25 000
Bay back period = 5 years
Over head expenses = 30% of the machine depreciation rate
Machine cost (M_1) = Machine depreciation rate + Machine over head
= \$[25000/5×240×8]×1.3/hr
= \$ 3.385/hr

3.2 Labour cost (*X*)

This component is made up of the operator's wage rate and overhead. The operator's overhead includes training costs, employer's CPF contributions, medical and other fringe benefits, which is estimated to be 60% of the wage rate. Wage rate is estimated to be \$ 15/hr and over heads are \$ 9/hr. The labour cost rate (*X*) is calculated to be \$ 24/hr.

3.3 Electricity cost (*E*)

Electricity charges are calculated based on power consumed per hour and cost per kWh.

Power consumed per hour = 230×32=7360 W
Unit cost = $ 0.17/kWh
Electricity cost (*E*) = $ [7.36×0.17]/hr
= $ 1.25/hr

3.4 Cost of electrolyte (C_1)

It is calculated by dividing the price of electrolyte (*P*) by the working time of the electrolyte (T_e).

$$\text{Cost of electrolyte } C_1 = \frac{P}{T_e} \tag{4}$$

=$ [0.10/0.2]/hr
=$ 0.5/hr

3.5 Cost of changing the electrolyte (C_2)

It is calculated by the following formula.
Cost of changing the electrolyte:

$$C_2 = \frac{X * T_z}{T_e}, \tag{5}$$

where, T_z - Changing time of the electrolyte (hr),
T_e -Working time of the electrolyte (hr)
C_2 =$ [24×0.167/0.2]/hr
=$ 20.04/hr

3.6 Cost of filter (C_3)

It is calculated by the eqn. (6):

$$C_4 = \frac{Y}{T_f}, \tag{6}$$

where, *Y* - Cost of the filter depreciation for a period between two cleaning operations ($)
T_f - Working time of filter (hr)
Initial cost of the filter = $ 20
Working time of the filter = 720 hr
No. of cleaning operations = 4
Y = initial cost of filter/(no. of cleaning operations+1)
Y = $ [20/(4+1)]
= $ 4
Cost of filter (C_3) = $ [4/720]/hr
= $ 0.0056/hr

3.7 Cost of filter cleaning (C_4)

It is calculated using the eqn. (7).

$$C_4 = \frac{X * T_w}{T_f}, \tag{7}$$

where, T_w is the changing time of the filter
C_4= $ [24×0.0833/720]/hr = $ 0.00278/hr

3.8 Tooling cost (C_5)

It is calculated by dividing the tool price by the tool life.

$$\text{Tooling cost } C_5 = \frac{T}{T_1}, \tag{8}$$

where, *T* -Tool price ($), T_1 -Tool life (hr).
Ideally during electro chemical machining, there is no tool wear. But in practice, occasional sparking causes damage in the tool and limits the tool life.
Therefore the tool life is expressed as:

$$T_1 = \frac{N}{nF}, \tag{9}$$

where, *N* - Number of allowable sparks for a given tool material.
n - Number of sparks produced during machining, *N*=3 sparks per minute, *n*=5 sparks per minute (average) in this work, Tooling cost values varies according to tool feed rate (*F*). Tool price (*T*) = $ 11 (tool is made up of copper material).

3.9 Tool changing cost (C_6)

It is calculated by multiplying the cost rate (*X*) by the tool changing time (T_c) and dividing by tool life (T_1). It depends on the tool feed rate (*F*).

$$C_6 = \frac{X * T_c}{T_1} \text{ /hr}, \tag{10}$$

3.10 Cost of non-productive time (C_7)

It includes the cost of loading and unloading the component. This cost is determined by adding all the non-productive time (T_i) and multiplying it by the cost rate(X). It is calculated to be $ 0.2 per hour.

$$C_7 = X * T_{i.} \tag{11}$$

Table 2. Experimental results

Trial Order	**C(A)**	**V(V)**	**U (l/min)**	**IEG (mm)**	**F (mm/min)**	**EC (g/l)**	**Cost per component $**	**Tolerance (mm)**
	x_1	x_2	x_3	x_4	x_5	x_6		
1	-1	1	1	1	1	-1	0.692	0.025
2	0	0	0	0	0	0	0.687	0.060
3	0	0	0	0	0	0	0.687	0.060
4	1	-1	-1	-1	1	-1	0.689	0.025
5	0	0	0	0	0	0	0.687	0.060
6	1	-1	1	-1	-1	-1	0.682	0.040
7	-1	1	1	-1	-1	-1	0.685	0.035
8	1	1	-1	1	-1	1	0.687	0.042
9	1	1	-1	-1	1	1	0.694	0.065
10	-1	-1	1	1	1	1	0.688	0.095
11	-1	-1	-1	-1	1	1	0.688	0.060
12	0	0	0	0	0	0	0.687	0.062
13	1	-1	-1	1	-1	-1	0.682	0.055
14	1	1	1	-1	-1	1	0.687	0.069
15	-1	-1	-1	1	-1	1	0.681	0.065
16	-1	1	-1	-1	1	-1	0.692	0.055
17	-1	-1	1	-1	-1	1	0.681	0.042
18	1	-1	1	1	1	-1	0.689	0.039
19	-1	1	-1	1	-1	-1	0.685	0.044
20	1	1	1	1	1	1	0.694	0.048
21	1	-1	-1	-1	-1	1	0.682	0.035
22	-1	-1	1	1	-1	-1	0.681	0.034
23	1	-1	1	-1	1	1	0.689	0.060
24	1	-1	-1	1	1	1	0.689	0.049
25	1	1	-1	-1	-1	-1	0.687	0.080
26	0	0	0	0	0	0	0.687	0.049
27	1	1	-1	1	1	-1	0.694	0.035
28	-1	-1	1	-1	1	-1	0.688	0.025
29	-1	1	-1	1	1	1	0.692	0.049
30	1	1	1	-1	1	-1	0.694	0.083
31	-1	-1	-1	-1	-1	-1	0.681	0.049
32	-1	1	1	1	-1	1	0.685	0.041
33	0	0	0	0	0	0	0.687	0.051
34	1	1	1	1	-1	-1	0.687	0.035
35	-1	1	1	-1	1	1	0.692	0.049
36	-1	1	-1	-1	-1	1	0.685	0.035
37	1	-1	1	1	-1	1	0.682	0.036
38	-1	-1	-1	1	1	-1	0.688	0.043
39	0	0	0	0	0	0	0.687	0.064
40	0	0	0	0	0	0	0.687	0.065
41	0	0	0	0	2	0	0.694	0.035
42	0	0	0	0	0	-2	0.687	0.035
43	-2	0	0	0	0	0	0.686	0.042
44	0	2	0	0	0	0	0.692	0.042
45	0	0	2	0	0	0	0.687	0.024
46	0	0	0	-2	0	0	0.687	0.025
47	0	0	0	0	0	2	0.687	0.033
48	2	0	0	0	0	0	0.688	0.031
49	0	0	-2	0	0	0	0.687	0.032
50	0	0	0	0	0	0	0.687	0.055
51	0	0	0	0	-2	0	0.680	0.043
52	0	0	0	2	0	0	0.687	0.025
53	0	-2	0	0	0	0	0.682	0.024
54	0	0	0	0	0	0	0.687	0.068

3.11 Material cost (C_8)

Some cost components such as the amount of non-productive time and material cost are ignored since they do not vary with tolerance. Total cost per component:

$$C_t = (M + E + C_1 + C_2 + C_3 + C_4 + C_5 + \\ +C_6)T_m + C_7 + C_8, \qquad (12)$$

where T_m – machining time. All the cost components are calculated for the machining time (T_m) of 180 seconds and the total cost per component is presented in Table 2.

4 Analysis of developed models

The analysis of variance (ANOVA) and the F-test were performed to identify the significance of developed mathematical models. The values of “Prob>F” that are less than 0.05 indicate the significance of the model terms since they construct 95% confidence level. The values greater than 0.1 indicate the model terms are not significant. The calculated value of F-ratio for lack of fit is to be compared with standard values in order to check the adequacy of the developed models. The F-ratio has been calculated as a ratio of mean sum of squares to mean sum of error. If the calculated F-ratio value is less than the standard, there is no strong evidence of lack of fit. If R^2 and R^2_{adj} values differ, there is a good chance that non-significant terms have been included in the model [12].

4.1 ANOVA analysis for cost model

The model F-value of 80123 implies that the model is significant. Values of “Prob > F” less than 0.05 indicate that model terms are significant. In this case C, V, F, EC, C^2, F^2, EC^2, $C×V$, $C×F$, $C×EC$ and $F×EC$ are significant model terms. Values greater than 0.1 indicate that the model terms are not significant. The coefficient of determination (R^2) is 0.99. This model can be used to navigate the design space.

$$Cost = 0.662 + 2.74\,X\,10^{-5} * C + 0.0166 * F + 1.34 * 10^{-5} * EC - 5.6\,X10^{-8} * C^2 - 3.12 * 10^{-4} * F^2 - 1.39\,X\,10^{-8} * EC^2 + 2.5 * 10^{-6} * C * V + 4.17\,X\,10^{-6} * C * F - 2.8\,X\,10^{-8} * C * EC - 2.1\,X\,10^{-6} * F * EC \qquad (13)$$

Table 3. ANOVA for Cost model

Source	*SS*	*DF*	*MS*	*F- value*	*Prob>F*	Significance
Model	$6.90e^{-4}$	27	$2.56e^{-5}$	80130	< 0.0001	Significant
C	$1.77e^{-5}$	1	$1.77e^{-5}$	55278	< 0.0001	
V	$2.21e^{-4}$	1	$2.21e^{-4}$	$6.90e^{5}$	< 0.0001	
F	$4.53e^{-4}$	1	$4.53e^{-4}$	$1.42e^{6}$	< 0.0001	
EC	$4.90e^{-8}$	1	$4.90e^{-8}$	153	< 0.0001	
C^2	$5.22e^{-9}$	1	$5.22e^{-9}$	16	0.0004	
F^2	$5.22e^{-9}$	1	$5.22e^{-9}$	16	0.0004	
EC^2	$5.22e^{-9}$	1	$5.22e^{-9}$	16	0.0004	
$C×V$	$7.20e^{-7}$	1	$7.20e^{-7}$	2250	< 0.0001	
$C×F$	$5.00e^{-9}$	1	$5.00e^{-9}$	16	0.0006	
$C×EC$	$5.00e^{-9}$	1	$5.00e^{-9}$	16	0.0006	
$F×EC$	$5.00e^{-9}$	1	$5.00e^{-9}$	16	0.0006	
Residual	$8.00e^{-9}$	25	$3.20e^{-10}$			
Lack of fit	$8.00e^{-9}$	17	$4.71e^{-10}$			
Pure Error	0	8	0			
Total	$6.92e^{-4}$	53				
SS-Sum of squares, ***DF***-Degrees of freedom, ***MS***-Mean square						

4.2 ANOVA analysis for Tolerance model

Table 4. ANOVA for Tolerance model

Source	SS	DF	MS	F-value	Prob>F	Significance
Model	$9.54e^{-3}$	27	$3.53e^{-4}$	4.55	0.0001	Significant
EC	$4.65e^{-4}$	1	$4.65e^{-4}$	5.99	0.0217	
U^2	$4.57e^{-4}$	1	$4.57e^{-4}$	5.89	0.0228	
IEG^2	$6.61e^{-4}$	1	$6.61e^{-4}$	8.52	0.0073	
$C\times V$	$1.27e^{-3}$	1	$1.27e^{-3}$	16.33	0.0004	
$C\times IEG$	$8.39e^{-4}$	1	$8.39e^{-4}$	10.80	0.0030	
$C\times EC$	$4.00e^{-4}$	1	$4.00e^{-4}$	5.16	0.0320	
$V\times IEG$	$1.70e^{-3}$	1	$1.70e^{-3}$	21.86	< 0.0001	
$V\times EC$	$4.84e^{-4}$	1	$4.84e^{-4}$	6.23	0.0195	
$U\times F$	$4.21e^{-4}$	1	$4.21e^{-4}$	5.42	0.0283	
$U\times EC$	$3.88e^{-4}$	1	$3.88e^{-4}$	5.00	0.0346	
$F\times EC$	$7.26e^{-4}$	1	$7.26e^{-4}$	9.35	0.0052	
Residual	$1.94e^{-3}$	25	$7.76e^{-5}$			
Lack of fit	$1.84e^{-3}$	17	$1.08e^{-4}$	8.31	0.0024	
Pure Error	$1.036e^{-4}$	8	$1.30e^{-5}$			
Total	0.014	53				

The model F-value of 4.55 implies that the model is significant. The values of “Prob > F” less than 0.05 indicate that model terms are significant. In this case, EC, U^2, IEG^2 , $C\times V$, $C\times IEG$, $C\times EC$, $V\times IEG$, $V\times EC$, $U\times F$, $U\times EC$ and $F\times EC$ are significant model terms. The coefficient of determination (R^2) is 0.83. This model can be used for further analysis.

$$Tolerance = -0.483 + 0.002848 * C - 0.00755 * V - 0.0124 * U + 0.002 * E - 0.000065 * C^2 - 0.000147 * V^2 - 0.0009245 * U^2 - 0.445 * IEG^2 - 0.021 * F^2 - 0.0000024 * EC^2 + 0.000105 * C * V + 0.0000833 * C * U - 0.0034 * C * IEG - 0.00046 * C * F - 0.0000079 * C * EC - 0.00004 * V * U - 0.018 * V * IEG - 0.0005 * V * F - 0.0000324 * V * EC - 0.005 * U * IEG + 0.0091 * U * F + 0.000058 * U * EC - 0.007 * IEG * F + 0.001 * IEG * EC + 0.000794 * F * EC \tag{14}$$

5 Main effects due to parameters

The main effects are assessed using the level average response analysis of the raw data. This analysis was done by averaging the raw data at each level of each parameter and plotting the values in graphical form. The level average responses from the raw data helps in the analysis of the trend of the performance characteristic with respect to the variation in the factor under study. Main effects of the process parameters on cost and tolerance are shown in Figs. 4 and 5. As shown in Fig. 4 and 5, at low current of 205 A, the production cost is low while tolerance is 0.0424 mm. As current is increased, cost and tolerance are also increased. This is due to the high current density which increases the rapid dissolution rate. At a higher flow rate of 15 l/min, both cost and tolerance show very good results. At higher voltage of 26 volts, the cost reaches the maximum value. But tolerance is reasonably good. At the lower voltage of 10 volts, cost and tolerance show good performance. Both performance measures show good values at lower IEG. The best value of IEG for all objectives is just about 0.1 mm. When feed rate is increased, both cost and tolerance will be increased. The best feed rate value for all output parameters is 0.2 mm/min. Concentration of NaCl affects the ECM performances largely. NaCl concentration of 100 grams per liter of water produces a good performance. This is due to sufficient molar conductance for complete ionization process, which in turn produces good engineering tolerance. The first (-2) and fifth level (+2) of observation is only a single value according to RSM design, its corresponding main parameter effect is largely decided by the cumulative effects of other parameters in the particular machining condition.

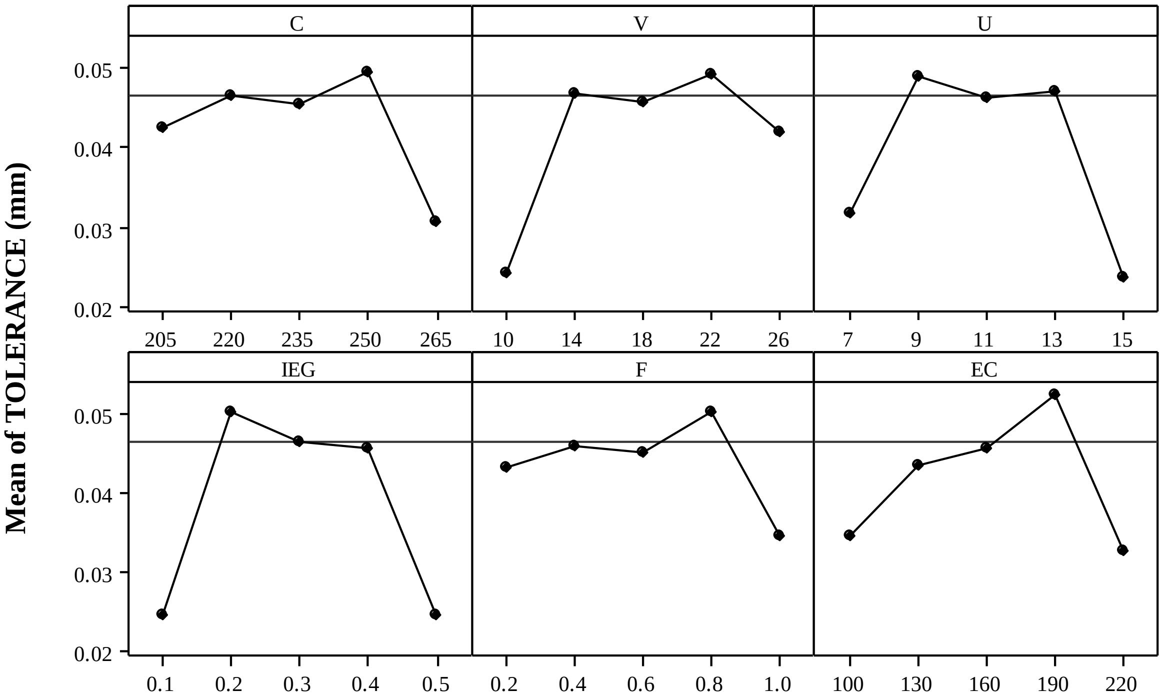

Figure 4. Main effects of parameters on tolerance.

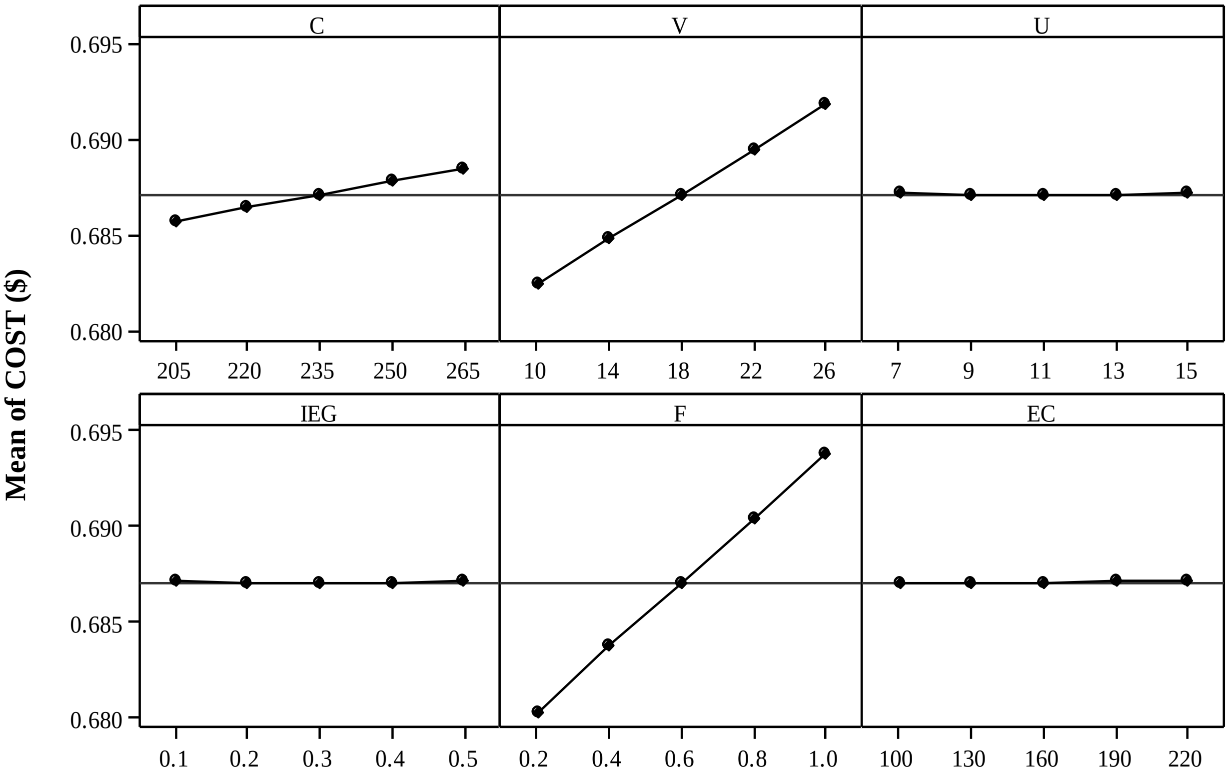

Figure 5. Main effects of parameters on cost.

6 Conclusion

An attempt has been made to understand the economic implications of electrochemical machining of 6061Al/10%wt Al2O3/5%wt SiC composite to produce a good engineering tolerance. The following conclusions have been made from the study.

1) The different elements of costs resulting from electrochemical machining of composite were considered to find out the production cost (per hour) for producing specific tolerance.
2) ANOVA test has been performed to understand the effect of ECM process parameters on performance measures i.e. cost and tolerance.
3) The process parameters such as current, voltage and feed rate significantly affect the cost while the outcome of tolerance depends on all the parameters.
4) Regression models were developed to represent the relationship between process parameters and the outcomes i.e. cost and tolerance.
5) The coefficient of determination (R2) for both models confirms that the developed models satisfy the real requirements necessary for electrochemical machining of 6061Al/10%wt Al2O3/5%wt SiC composite.

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