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Response Surface Methodology and Desirability Analysis for OptimizingµWEDMParameters for Al6351/20%Al_2O_3 composite

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Abstract: The application of metal matrix composites (MMCs) in biosensorshasdiverted the research attention towards the unconventional process of micro wire electrical discharge machining(µWEDM). The orthodox method of machining these composites is observed to create excessive tool wear and consume more tool cost. The requirement of intricate profiles in MMC sensorsat a desired level of surface finish, poses a great challengein the selection of machining parameters in µWEDM. The paper explores the vigour of response surface methodology and desirability analysis in identifying the optimal machining parameter combination for achieving thepreferredsurface finish with Al6351/20%Al_2O_3 composite. Taguchi's L_{18} orthogonalarray is used for experimentation and the optimal settings are validated through the confirmation test.
Keywords:Taguchi, Response surface methodology,µWEDM,Al6351/20% Al_2O_3, Optimization, Desirability analysis.

1 Introduction

The micro wire electrical discharge machining (µWEDM) is an unconventional material removing process employed for machining complex profiles. The process uses a wire electrode under tension creating the desired sparks for machining. The process is characterized by the absence of direct contact between the wire and work piece resulting in lesser mechanical stress [1]. The higher density of sparks removes material from the wire electrode as well. In a majority of machines, the horizontal table movement is controlled by CNC making it possible to machine any three dimensional profile. A proper control over the process can be established by identifying the optimal level of machining parameters, particularly in miniaturization and integration of the micromechanical components, which is an important area of research with metal matrix composites.

The µWEDM was observed as a multi input process and optimal combination of machining parameters can be sorted out by using techniques like the artificial neural networks (ANN), genetic algorithm (GA), principal component analysis (PCA), grey relational analysis (GRA), fuzzy logic and response surface methodology (RSM). Application of ANN and GA was observed to be effective in optimizing the machining parameters [2].The optimization could also be performed by using a combined approach of GRA and PCA[3]. The technique for order of preference by similarity to ideal solution (TOPSIS) was used effectively to find the optimal setting of input parameters in a hybrid format along with GRA [4]. Generally in µWEDM process, material removal rate and surface finish were observed as the quality characteristics [5, 6, 7].

The RSM employs a statistical procedure for modelling the responses, which could be optimized using the desirability analysis [8]. Generally central composite design (CCD) was used in experimentation and the response surface plots were obtained to study the effects of various input parameters on the responses [9, 10, 11]. The desirability analysis was also found to yield good results in finding the optimal input conditions [12,13]. The Box–Behnken design based analysis could also predict near optimal condition within the experimental domain but only with excessive number of experimental trials [14]. Taguchi's orthogonal array was used for experimentation and methods based on Taguchi techniques were observed to be effective as well [15, 16].

From the literature, it was observed that little attention was given to the optimization of µWEDM process parameters, especially when applied to MMCs. Further the usage of RSM in µWEDMwas also scarce. Hence an attempt was made to employ RSM and desirability analysis for optimizing the µWEDM parameters for Al6351/20%Al_2O_3 composite.

2 Material and Method

The parent material used was Al6351/20%Al_2O_3 composite in the form of rectangular sheets of dimension 25 cm x 25mm x 6mm. A copper wire of diameter80µm was used for machining using an automated machining system. The machining parameters like voltage (V), capacitance (C), feed (F) and tension of the wire (WT) were included in the study and surface roughness (SR) was observed after each trial machining. The machining parameters were selected based on the literature [1, 5-7] and three levels were chosen for each parameter during experimentation. The experiments were conducted using Taguchi's L_{18}orthogonal array in a DT-110 three-axis automatic multi-process integrated micromachining system. The micromachining system was flexible for the hybrid processesincluding wire electro discharge grinding (W-EDG) and electro chemical machining (ECM). The machining trials were conducted at random to remove the extraneous effects and response obtained during each trial is listed in Table 1.

Table1 L_{18} array displaying the experimental settings and obtained responses

Trials	Control parameters				Response
	V (volts)	C (x 10^{-8} F)	F (µm/Sec)	WT (g)	SR
1	85	10	4	10	0.678
2	85	20	8	15	1.092
3	85	30	12	20	2.936
4	95	10	4	15	0.872
5	95	20	8	20	3.112
6	95	30	12	10	1.389
7	105	10	8	10	2.013
8	105	20	12	15	1.919
9	105	30	4	20	3.421
10	85	10	12	20	2.397
11	85	20	4	10	0.597
12	85	30	8	15	0.826
13	95	10	8	20	3.175
14	95	20	12	10	1.739
15	95	30	4	15	1.252
16	105	10	12	15	1.411
17	105	20	4	20	2.983
18	105	30	8	10	2.098

3 Response Surface Methodology

Optimization of surface finish in the process of discharge machining of Al6351/20%Al_2O_3 composite was more complex and RSM was applied to sort out the model for SR and desirability analysis was used to identify the optimal parameter combination using the steps described below.

Step 1: Develop a polynomial equation of second order for SR (quadratic model) to link the inputs to the responses.
Step 2: Generate the analysis of variance (ANOVA) table for SR values to supplement RSM.
Step 3: Generate the response plots for different combination of the input parameters.
Step 4: Determine the optimal level from desirability analysis.

Step 5: Conduct the confirmation test for validation.

4 Results and Discussion

4.1. Mathematical model for SR

The mathematical modelling for SR (Eq. 1) was used to study the machining performance and understand the intricacies in the system. The developed model was used to explore the individual and interaction effects of the µWEDMparameters on SR. The model coefficients were obtained using Design Expert (version 7.0)software.The results of ANOVA on surface roughness (Table 2)prove the statistical significance of the developed model.

Table 2 ANOVA table for SR

Source	Sum of Squares	Degrees of freedom	Mean Square	F Value	p-value Prob> F	significant
Model	14.6574	10	1.46575	35.1616	< 0.0001	
A-Voltage (V)	4.6690	1	4.6690	112.0054	< 0.0001	
B-Capacitance (C)	0.1337	1	0.1337	3.2076	0.1164	
C-Feed (F)	3.0914	1	3.0914	74.1606	< 0.0001	
D-Wire tension	0.1087	1	0.1087	2.6071	0.1504	
AC	3.8638	1	3.8638	92.6900	< 0.0001	
AD	2.6913	1	2.6913	64.5622	< 0.0001	
BD	0.1224	1	0.1224	2.9365	0.1303	
CD	2.7542	1	2.7542	66.0700	< 0.0001	
A^2	1.9478	1	1.9478	46.7268	0.0002	
C^2	2.5839	1	2.5839	61.9854	0.0001	
Residual	0.2918	7	0.0417			
Cor Total	14.9491	17				

The importance of quadratic model for SRwas confirmed by the model p-value (<0.0001). The closeness of the R-squared value (0.9805) to unity (Table 3)display a better fitness between the actual SR and the one obtained from the response model. The predicted and adjusted R-squared values were in good agreement with each other proving the fitness of the experimental data to generated mathematical model. The adequate model discrimination was also clearly visualized from the value of adequate precision (16.9624), greater than 4. Hence the generated model for the surface finish could be deemed fit and adequate in representing the machining conditions in µWEDM process.

Table 3 Table showing the R-squared and the adequate precision values

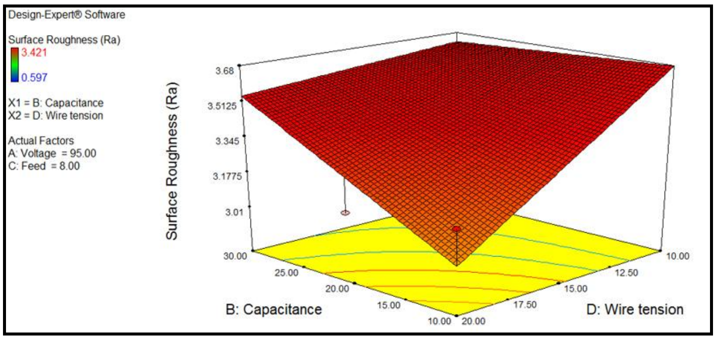
Std.	0.2042	R-Squared	0.9805
Mean	1.8839	Adjusted R-Squared	0.9526
C.V.	10.8377	Predicted R-Squared	0.8950
PRESS	1.5694	Adequate Precision	16.9624

$$SR = -88.93450+2.10546 * Voltage\ (V) -0.030661 * Capacitance\ (C) +4.70798 * Feed\ (F) -4.52952 * Wire\ tension\ (WT) -0.049142 * Voltage\ (V) * Feed\ (F) +0.038279 * Voltage\ (V) * Wire\ tension\ (WT) +2.85667E-003 * Capacitance\ (C) * Wire\ tension\ (WT) +0.099728 * Feed\ (F) * Wire\ tension\ (WT) -0.011276 * Voltage\ (V)^2 -0.077865 * Feed\ (F)^2 \quad (1)$$

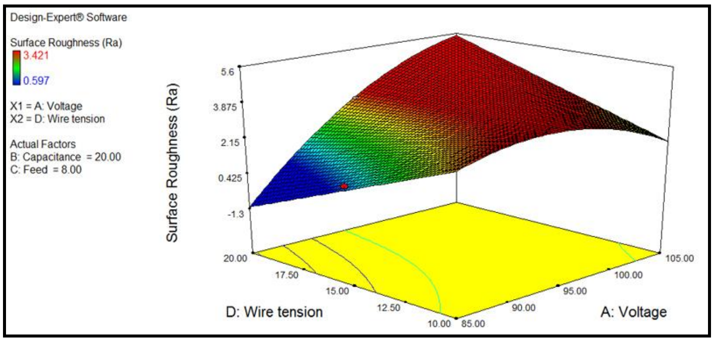
4.2 Study of response surfaces

The three dimensional plots were developed by relating the various machining parameters to the surface roughness. A higher level of capacitance and a lower level of feed and voltage were desired for the better SR while a moderate level of wire tension was observed to yield better surface finish Fig. (1)(a-d). Gap voltage assist in breaking the barrier between the wire and workpiece enabling the sparks to travel with ease and introduce the necessary thermal energy for melting and vaporizing the material. The wire tension reduces the amplitude of wire vibration,ensuring a smooth repetition of sparks. The capacitance ensures the build-up of the gap voltage to maximum value in one step to produce good finish.

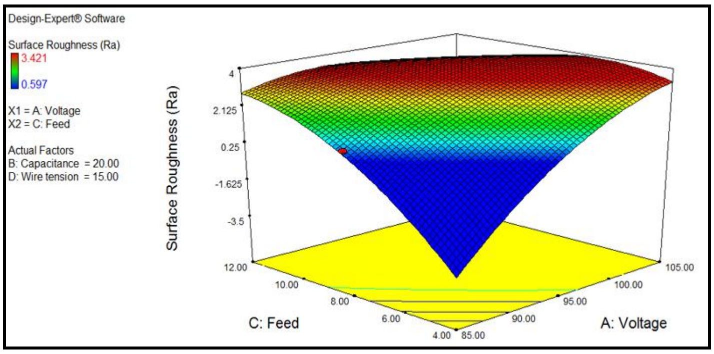
(a)



(b)



(c)



(d)

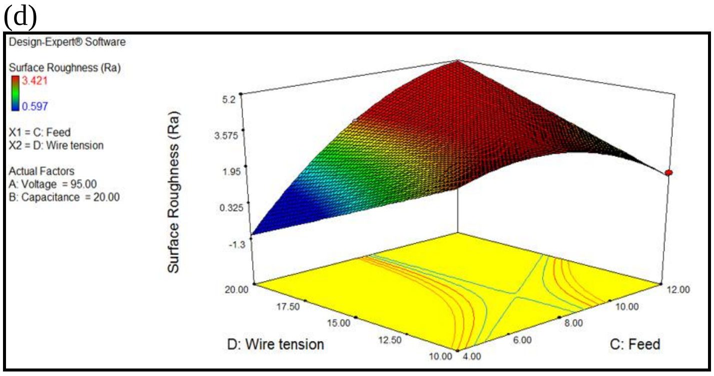


Figure 1 (a), (b), (c), (d) three dimensional response plots.

4.3 Ramp function graph

The desirability values for the responses are shown in Figure2.The dot on each ramp indicates the optimal level of that parameter. Accordingly the optimal level was chosen as $A_1B_3C_1D_2$. The height at which the dot was located indicates the amount of desirability. The desirability value varies between 0 and 1 depending on the proximity of the outputs towards the target. The proximity between the actual and model values of SR wasclearly evident from Figure3. The vicinity of the distributed points towards the centre line indicates their proximity.

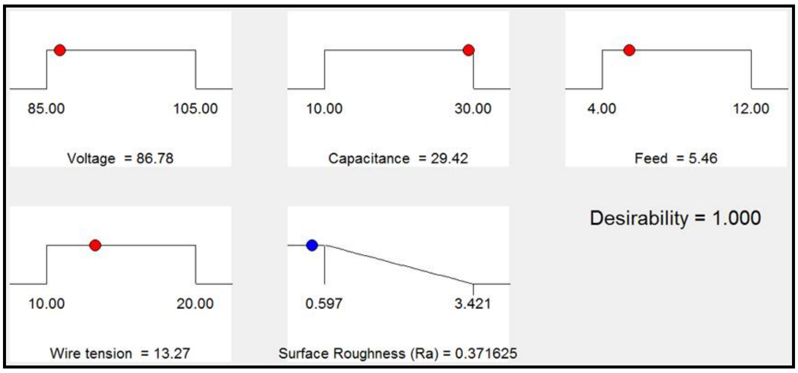


Figure 2 Ramp function graph

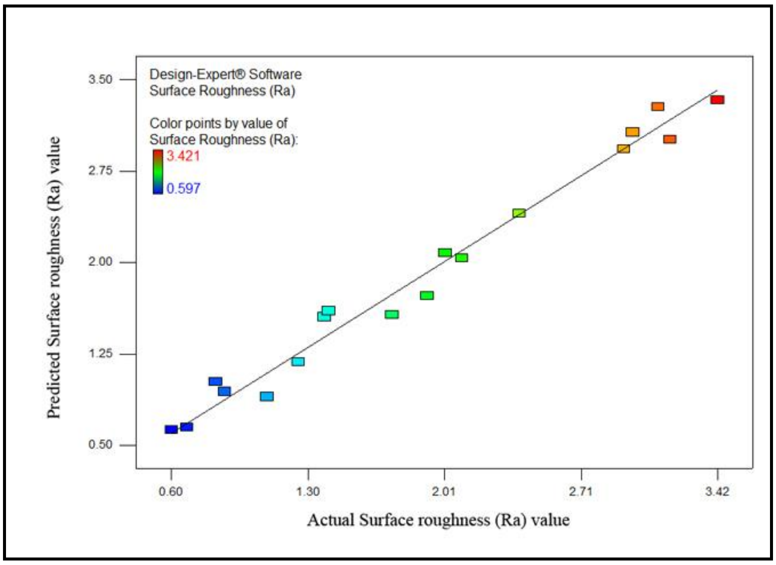


Figure 3 Plot of the actual versus the predicted values of SR

4.4. Desirability analysis

Desirability analysis was performed by employing the design expert software using the *larger-the-better* desirability function for SR values. From the desirability analysis, the optimal level of various µWEDM parameters were found and listed in Table 4. The optimal level was selected as $A_1B_3C_1D_2$(V=86.78 V, C=29.41x10^{-8}F, F=5.46 µm/s, WT=13.27 g).

Table 4 Optimal level obtained from the desirability analysis

Factor	**Name**	**Optimal level**	**Low Level**	**High Level**
V	Voltage	86.7764	85	105
C	Capacitance	29.4173	10	30
F	Feed	5.4597	4	12
WT	Wire tension	13.2693	10	20
Response	Prediction	SE Mean	95% CI low	95% CI high
Surface Roughness	0.3716	0.1418	0.0364	0.7068

4.5.Validation test

After obtaining the optimal µWEDM parameter setting, the next step was to compare the SR obtained with the optimal setting (V=86.78 V, C=29.41x10^{-8}F, F=5.46 µm/s, WT=13.27 g) and the initial setting of parameters. It was found that the surface roughness value was hugely reduced for the optimal combination predicted RSM methodology (Table 5). The validation test ensures the suitability of application of RSM in various machining processes.

Table 5 Results of validation test

Responses	Initial Setting		RSM setting		Improvement in response
	Predicted Value	Observed value	Predicted Value	Observed value	
Surface roughness	0.653	0.597	0.372	0.419	**0.178**
Parameter settings	$A_1B_2C_1D_1$		**V=86.78 V, C=29.41x10^{-8}F, F=5.46 µm/s, WT=13.27 g**		**29.82%**

5 Conclusion

The report discloses the application of RSM to the machining of Al6351/20%Al_2O_3 composite using µWEDM process. The following conclusions were drawn.

- The RSM method was used to create a model for SR in terms of machining parameters, their square terms and parameter interactions.
- The SR values from the experimental domain and predicted values matched well demonstrating a better model fitness and adequacy.
- Enhanced capacitance was found to produce a better surface finish, while a lower level of feed and voltage was observed to produce similar results.
- The research findings will offer guidelines to obtain a good surface finish in machining Al6351/20%Al_2O_3 composite using µWEDM process.

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