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Original Article

Electrochemical drilling and multi response optimization using different methods of assigning weights to the responses for sustainable machining of AA6061-TiB_2 in-situ composites

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Abstract

The current paper describes the multiple response optimization of electrochemical machining (ECM) responses, such as specific energy consumption (SEC), overcut, and material removal rate (MRR), aimed at sustainable machining. The experimental work was conducted on electrochemical drilling of AA6061-TiB_2 composite material. The concentration of electrolyte, applied voltage, and current were selected as the governing parameters in machining process. The Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) was applied to identify the optimal set of machining parameters based on the closeness coefficient (CC). The weighting of responses was allotted by using the Analytical hierarchy process (AHP), or equal weights, or entropy method. The results indicate that the closeness coefficient varied by weighting. A comparative analysis of the confirmation experiments showed that the optimal level of machining parameters obtained from the entropy weighting method gave the largest improvement in the closeness coefficient to attain sustainable machining.

Keywords: electrochemical machining, in-situ composites, sustainable machining, multiple response optimization, response weighting method

1. Introduction

Recently, the mixed salt chemical reaction method of manufacturing aluminum-based in-situ composites has received widespread attention among researchers (Mozammil, Karloopia, Verma, & Jha. 2020). Amongst the numerous in-situ composites, Al-TiB_2 composites are extensively discussed in past studies. The chemically formed TiB_2 turns into a non-homogeneous nucleation spot throughout the solidification of aluminum alloy and enables grain refinement (Pramod, Bakshi, & Murty 2015). ECM is a most suitable process for machining the hard-to-cut materials to intricate shapes (Xu & Wang, 2019). However, electrochemical dissolution generates a huge volume of sludge containing metal ions, nitrate, acids, and traces of heavy metals. Disposal of these sludges is associated with numerous environmental problems. Mortazari & Invanov (2019) also established a sustainability assessment indicator for the electrochemical machining process. Kozak, Ross, & Rozenek (1996) state that the energy consumption by the ECM is from 2 to 7 x 10 ^{5} J/cm^2; whereas the energy consumption for the turning process is from 1.7 to 3 x 10 ^{5} J/cm^2. Hence, the greater energy consumption of ECM restricts its widespread application in industries and needs a sustainability assessment.

Multi-response optimization offers reasonable correlations among the heterogeneous responses and aids achieving a single optimal set of governing parameters that fulfill the process specifications for all responses (Bagaber & Yusoff 2019; Udomboonyanupap, Siwadamrongpong, Muttamara, & Pangjundee 2020). The utilization of multiple response optimization to reduce manufacturing costs and environmental issues in the area of conventional machining is well documented in the literature. Assignment of weights to machining responses is a crucial task and a wrong assignment of weights causes inaccuracy in the process governing parameters identified as optimal choices. However, the real-time industrial practice is to either weigh the responses based

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on the necessity of the manufacturing industry, or else based on requirements of the given process. Kumar, Bilga, & Singh (2017) used the analytical hierarchy process for weighting the responses and TOPSIS method to identify the experimental trial with minimal power factor, cutting power, cutting energy, and energy efficiency in turning EN 353steel. A closer look at the literature concerning the sustainability assessment for ECM of the aluminum composites, however, reveals several gaps and shortcomings. Experiment based sustainability assessment for ECM process in terms of SEC, overcut and MRR has not been reported. Further, there is no past study that has described the trade-off between energy, quality, and cost-related responses in ECM of aluminum composites. In general, the ECM process consumes a comparatively large amount of energy for removing a unit volume of the material. Therefore, a systematic investigation is required for addressing the selection of weights assigned to the responses during multiple response optimization. The current paper addresses multiple response optimization of electrochemical drilling process governing parameters to minimize the SEC and overcut, and to maximize the MRR by using AHP, equal, and entropy weights integrated with TOPSIS method during sustainable machining of AA6061-TiB_2 composites, so far lacking in the scientific literature.

2. Materials and Methods

The AA6061 alloy was used as matrix material for manufacturing the composite. Mixed salt synthesis was used to produce the TiB_2 ceramic particles by conducting a reaction among the K_2TiF_6 and KBF_4 salts, and molten aluminum. The processing and characterization of the AA6061-5%TiB_2 in-situ composite are reported in our earlier work (Chandrasekhar & Prasad, 2018). The microstructure of the fabricated composite is illustrated in Figure 1. The inclusion of chemically generated TiB_2 facilitates grain refinement. Refined aluminum grains are observed in the microstructure. The composite was finished into a 0.5-mm sheet used in the investigation. An ECM experimental setup (Sona College of Technology, Salem, India) exemplified in Figure 2 was used for experiments. The pulsed control system includes a pulsed power supply of 20 V and 30 A, with the provision for changing current, voltage, and pulse duration as needed. The duty cycle for the present work is fixed at 65% whereas the frequency of the pulsed control system is maintained at 50 Hz. The tool-workpiece gap was set at 50 µm. Current, voltage, and electrolyte concentrations were used as manipulated machining parameters, while SEC, MRR, and overcutting were the responses. A cylindrical tool made of copper with a size of Ø 500µm was selected, and $NaNO_3$ electrolyte was preferred for the experimental investigation. The rate of flow of electrolyte was fixed at 10 L/min for the machining. The MRR was estimated as the ratio of mass loss to the time taken for machining. Overcutting of the electrochemically drilled hole was measured using a metallurgical microscope. It is defined as half of the deviation between the hole size and tool diameter. SEC is the energy required to remove a unit volume of material. It may be defined as the ratio of electrical energy consumed to volume of material removed during the electrochemical dissolution. The electrical energy consumed by the ECM is computed by multiplying the applied voltage, current, and time of machining. The volume of material

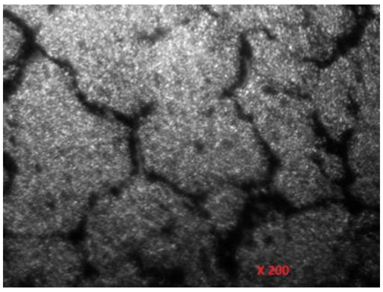

Figure 1. Optical microscopy of the Al-TiB2 composite

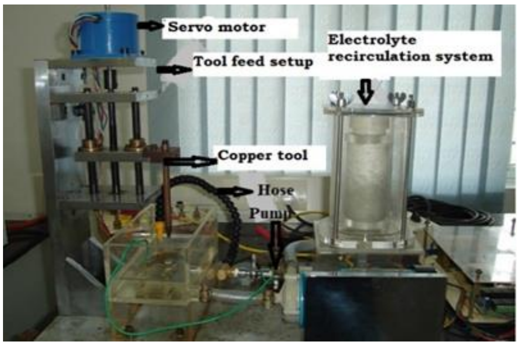

Figure 2. Electrochemical machining setup

removed is the mass loss divided by density. Process governing parameters and their levels are summarized in Table 1. L_{27} experimental layout was used in the experimental investigation. Machining responses from each experimental run were estimated based on the aforesaid procedure and are reported in the experimental layout in Table 1. Each experimental run was conducted two times and the averages are reported. Most of the investigators will assign equal weights to responses in multiple response optimization. However, the priority of sustainable responses should be larger for sustainable machining. In the AHP method, the weight of each response is estimated based on judgments of the choice maker. The equal weight method offers equal weighting of all responses, and the weight is 1 divided by the number of responses. The entropy method is an objective-based weighting method and can be utilized for eliminating man-made uncertainties and provide unbiased results. TOPSIS is a multiple response optimization method, which allows the negotiation between various responses, where a poor result in one response can be equalized by a good result in another response. This method was employed to rank the experimental trials. SEC and overcut are smaller is better type responses whereas the MRR is greater is better type response.

3. Results and Discussion

3.1 Weighting of responses

In the Entropy weighting method as described by Dev, Aherwar, & Patnaik (2019), the projection value, entropy, dispersion, and weights of the responses were evaluated. The Entropy weighing assigned weights for SEC, overcut and MRR are 0.4905, 0.00058, and 0.5088

Table 1. Experimental design and closeness coefficient

Trial No.	Levels			Responses			AHP weights			
	Electrolyte Concentration (EC)	Voltage (V)	Current (C)	SEC X 10^5 (J/cm^2)	ROC (μm)	MRR (mg/min)	(S^+)	(S^-)	CC	Rank
1	1	14	2	5.873	50.556	0.029	0.0133	0.0835	0.86264	6
2	1	14	3	8.254	50.5652	0.031	0.0459	0.0441	0.48960	14
3	1	14	4	10.265	50.5722	0.037	0.0783	0.0112	0.12554	25
4	1	16	2	6.204	50.5658	0.028	0.0165	0.0780	0.82574	8
5	1	16	3	8.672	50.575	0.032	0.0526	0.0372	0.41416	17
6	1	16	4	10.716	50.5822	0.044	0.0855	0.0068	0.07376	26
7	1	18	2	6.409	50.5685	0.029	0.0185	0.0746	0.80090	9
8	1	18	3	8.899	50.5778	0.038	0.0558	0.0336	0.37547	18
9	1	18	4	10.913	50.585	0.043	0.0888	0.0056	0.05933	27
10	2	14	2	5.726	50.5315	0.033	0.0111	0.0859	0.88540	3
11	2	14	3	8.032	50.571	0.04	0.0416	0.0479	0.53550	11
12	2	14	4	9.969	50.5778	0.048	0.0730	0.0173	0.19180	21
13	2	16	2	6.035	50.5715	0.039	0.0115	0.0809	0.87540	5
14	2	16	3	8.417	50.5808	0.048	0.0474	0.0420	0.46966	15
15	2	16	4	10.377	50.588	0.062	0.0796	0.0155	0.16287	23
16	2	18	2	6.218	50.574	0.035	0.0147	0.0778	0.84104	7
17	2	18	3	8.613	50.5835	0.049	0.0506	0.0389	0.43454	16
18	2	18	4	10.532	50.5905	0.056	0.0822	0.0122	0.12932	24
19	3	14	2	5.577	50.5668	0.033	**0.0108***	**0.0884***	**0.89093***	**1***
20	3	14	3	7.810	50.5762	0.042	0.0378	0.0517	0.57739	10
21	3	14	4	9.672	50.583	0.043	0.0683	0.0213	0.23773	19
22	3	16	2	5.866	50.577	0.037	0.0105	0.0837	0.88827	2
23	3	16	3	8.163	50.5862	0.048	0.0433	0.0462	0.51623	12
24	3	16	4	10.038	50.5932	0.055	0.0740	0.0176	0.19250	20
25	3	18	2	6.028	50.5795	0.04	0.0112	0.0811	0.87900	4
26	3	18	3	8.327	50.589	0.057	0.0457	0.0442	0.49162	13
27	3	18	4	10.151	50.5958	0.056	0.0759	0.0164	0.17760	22

Table 1. Continued.

Trial No.	Equal weights				Entropy weights			
	(S^+)	(S^-)	CC	Rank	(S^+)	(S^-)	CC	Rank
1	0.0492	0.0384	0.43836	16	0.07528	0.05665	0.42938	17
2	0.0505	0.0207	0.29114	25	0.07678	0.03063	0.28517	25
3	0.0516	0.0143	0.21685	27	0.07758	0.02176	0.21906	27
4	0.0509	0.0359	0.41344	19	0.07781	0.05288	0.40465	19
5	0.0505	0.0181	0.26353	26	0.0767	0.02677	0.25875	26
6	0.0474	0.0239	0.33484	22	0.07081	0.03653	0.34033	22
7	0.0496	0.0343	0.40924	20	0.07579	0.05064	0.40055	20
8	0.0438	0.0214	0.32804	23	0.06621	0.03211	0.32659	23
9	0.0495	0.0223	0.31091	24	0.07394	0.03419	0.31617	24
10	0.0432	0.0402	0.48191	13	0.06611	0.05936	0.47308	14
11	0.0377	0.0283	0.42859	18	0.05722	0.04237	0.42542	18
12	0.0394	0.0306	0.43743	17	0.05875	0.0468	0.44339	16
13	0.0344	0.0406	0.54107	6	0.05267	0.06025	0.53357	9
14	0.0300	0.0353	0.54044	7	0.04512	0.05351	0.54252	7
15	0.0366	0.0508	0.58159	2	0.05391	0.07772	0.59043	2
16	0.0405	0.0372	0.47896	14	0.06195	0.05509	0.47068	15
17	0.0301	0.0358	0.54311	5	0.04517	0.05439	0.54627	6
18	0.0388	0.0418	0.51881	11	0.05731	0.06396	0.52741	10
19	0.0432	0.0413	0.48885	12	0.06609	0.06101	0.47999	12
20	0.0343	0.0315	0.47885	15	0.05202	0.04725	0.47597	13
21	0.0421	0.0242	0.36549	21	0.06317	0.03692	0.36883	21
22	0.0373	0.0407	0.52182	10	0.05707	0.06029	0.51371	11
23	0.0287	0.0364	0.55935	3	0.04315	0.05506	0.56062	3
24	0.0355	0.0408	0.53425	9	0.05259	0.06231	0.54233	8
25	0.0329	0.0413	0.55608	4	0.05039	0.06131	0.54886	4
26	**0.0222**	**0.0475**	**0.68109**	**1***	**0.03292**	**0.07219**	**0.68677**	**1***
27	0.0360	0.0421	0.53938	8	0.05316	0.06438	0.54774	5

respectively. By using the AHP method (Saaty, 2008), the relative normalized weight, consistency ratio, consistency index, and weighting of the responses were evaluated. AHP gave the weights for SEC, overcut and MRR as 0.7235, 0.1932, and 0.0833, respectively. In consistency analysis the calculated CR was less than the permissible 0.10, which confirmed good consistency in the judgments made by the decision-maker while assigning values in the pairwise comparison matrix. In the Equal weight method, the weights were all set to 1 divided by the number of responses, meaning 0.333 for all responses.

3.2 TOPSIS method

By using the TOPSIS method (Kumar et al. 2017), the weighted normalized matrix for the responses was constructed by using the weights from AHP, equal, and entropy weighting methods. Further, the positive and negative ideal solutions, separation measures, and closeness coefficient for each trial were calculated and are summarized in Table 1. As per the TOPSIS procedure, a greater closeness coefficient indicates that the corresponding experimental trial is comparatively better, while lesser values are worse.

As seen in Table 1, the experimental run 19 (T-19) for the AHP method had the largest closeness coefficient. The corresponding machining parameters were 3 molar electrolyte concentration, 14 V applied voltage, and 2 A current. Table 1 also shows that experimental run 26 (T-26) gave the largest closeness coefficient for equal and entropy weights. The corresponding machining parameters are 3 molar electrolyte concentration, 18 V applied voltage, and 3 A current. However, there is a slight change in the ranking of choices due to changed weight assignments.

3.3 Response graph and analysis of variance

To assess the influences of all governing parameters in electrochemical drilling on the overall responses, a response graph for the average closeness coefficient was generated by using Minitab 19 software. The mean values of the closeness coefficient obtained with AHP, equal, and entropy weights integrated with TOPSIS method at various levels of process control parameters are shown in Figures 3-5. Figure 3 shows that increasing electrolyte concentration increased the average closeness coefficient, whereas an increasing applied voltage and current reduced the average closeness coefficient. Further, Figure 3 also demonstrates that the current had the largest effect on the closeness coefficient from AHP weighting, followed by electrolyte concentration and voltage. The Response graphs in Figures 4-5 also exemplify that increasing electrolyte concentration and voltage increased the average closeness coefficient, whereas increasing current reduced the average closeness coefficient. Further, Figures 4-5 also indicate that the electrolyte concentration had an extreme effect on the closeness coefficient from equal and entropy weighting, followed by voltage and current. Analysis of variance was also performed to identify the contributions of each ECM parameter on the overall responses, and is summarized in Table 2. It is evident that the percentage contribution of current was 96.96 % while using AHP weights. With equal weights, the percentage contribution of electrolyte concentration was 68.17 %.Furthermore, the percentage contribution with entropy weights was also approximately similar to that with equal weights. It is clear from the analysis of variance that the weight assignments to responses make a significant difference in the contributions of the ECM parameters. The regression equations for AHP, equal, and entropy weight methods were fit by using Minitab-19, and are summarized in Table 3.

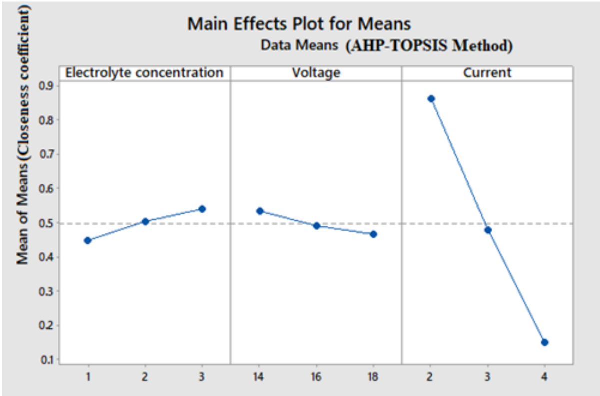

Figure 3. Response graph for AHP-TOPSIS method

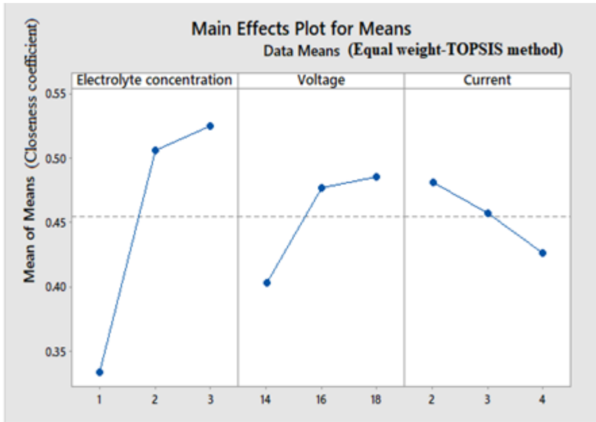

Figure 4. Response graph for Equal weight-TOPSIS method

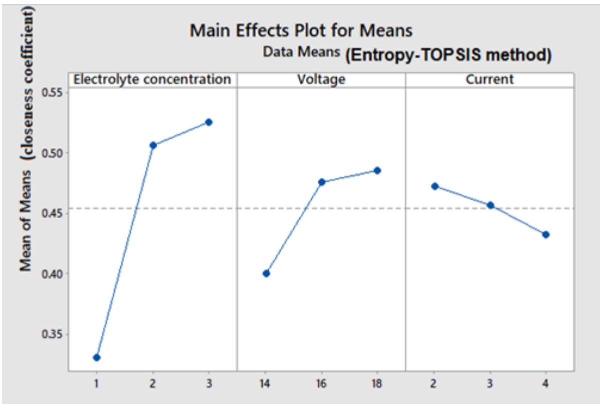

Figure 5. Response graph for Entropy-TOPSIS method

Table 2. Analysis of variance

Source	AHP weights	Equal weights	Entropy weights
	Percentage of contribution	Percentage of contribution	Percentage of contribution
Electrolyte concentration	1.608269395	68.17043	69.36327284
Voltage	0.874680307	18.04511	16.579514
Current	96.9629156	9.022556	8.951091972
Error	0.55370844	4.761905	5.106121193
Total	100	100	100

Table 3. Regression equations

AHP weight	Equal weight	Entropy weight
CC = 1.7414 + 0.04578 EC - 0.01688 V - 0.35549 C	CC = 0.018 + 0.0955 EC + 0.02050 V - 0.0272 C	CC = 0.023 + 0.0969 EC + 0.02141 V - 0.0199 C

3.4 Confirmation experiments

A confirmation experiment was performed to confirm the accuracy of the optimized parameters. Furthermore, the confirmation experiment also helps to compute the improvement in performance characteristics from optimal parameter settings over the initial parameter settings. Taguchi predictor from Minitab 19 software was used to predict the closeness coefficient under varied combinations of electrolyte concentration, applied voltage, and current. The closeness coefficients from prediction, experimental, and initial run with AHP, equal, and entropy weightings integrated with TOPSIS methods are summarized in Table 4. The predicted closeness coefficient had very small deviations from its experimental values, regardless of the weighting method. Table 4 also shows that the entropy integrated TOPSIS method had the greatest (37.47%) improvement in closeness coefficient among the tested weighting methods. Further, the equal weights with TOPSIS method gave a 35.63 % improvement, while AHP integrated with TOPSIS only gave a 3.14 % improvement in the closeness coefficient. The entropy integrated with TOPSIS method gave 18 V as the optimal voltage for sustainable machining. 18 V is a high voltage level, as the pulsed power supply system confines the period with power and curtails the current density in the machining area, and this could be considered as an additional cause for reduced overcutting, aside from improved quality of the drilled hole. Further, the application of a high voltage at 18 V is also a major factor reducing machining time and helps reduce the SEC. The use of sodium nitrate electrolyte pauses the stray corrosion and provides a close replication of the tool shape. It is considered a beneficial aspect for preserving the cylindricity of the hole. The entropy integrated with TOPSIS method also gave a 3 molar electrolyte concentration, contributing to the overall sustainable machining performance. As described by Wang, Peng, Yao, & Zhang (2009) a higher concentration of electrolyte delivers increased electrical conductivity and releases more ions for the chemical reactions. This supports faster rate of machining. Nevertheless, this effect does not offer much influence on overcutting and deviation from cylindricity of an electrochemically drilled hole, beside the SEC (Bhattacharyya & Munda, 2003). Further, the entropy integrated with TOPSIS method yielded 3 A as the optimal current for accomplishing sustainable machining efficiency. It is a moderate value amongst the tested levels of process parameters. According to Joule's first law, the heat generated in the machining area is directly proportional to square of the current, duration of current, and electrical resistance (Lienhard & Eichhorn, 1981). A moderate current induces reasonable heat, thereby maximizes the temperature in the electrolyte, which in turn increases electrical conductivity. This raises the rate of dissolution and enables faster machining under a constant supply of voltage. Nonetheless, the pulsed power supply system brings a necessary resolution to controlling overcutting and hole cylindricity during the machining.

3.5 Scanning electron microscopy

Figure 6 exemplifies the scanning electron microscopy assessment of micro-holes drilled at optimum process governing parameters (T-26) ie. 3 molar electrolyte concentration, 18 V applied voltage, and 3 A current. Figure 6 also shows that the radius of the hole is approximately constant through the periphery. Further, the edge of the hole has a nano-sized burr formed by current due to the lack of insulation throughout the tool. Salt and debris deposition are also noted nearby the hole. The high 18 V voltage and 3 A current along with pulsed power significantly influenced the rate of material dissolution without affecting the hole quality, apart from nano-sized delamination and burrs.

From the assessments of response graph, analysis of variance, confirmation experiments, and microscope of the drilled holes, the sustainability aspect of machining is not relying upon the SEC. Entropy weighting facilitated the role of SEC and how this response is interlinked with overcut and rate of material removal. Generally, the rate of machining is considered an economy oriented response. The present investigation indicates that the rate of machining offers a greater influence on sustainable machining than SEC. Further, electrochemical drilling by selecting lower level electrical parameters for a longer time will negatively impact the sustainability of machining. Therefore, the entropy method neglects slower rates of machining and offers a slightly larger weight to the rate of machining than to the SEC. The optimized process governing parameters are valid only for sustainable machining practice. Similarly, the weight assignment will be different for attaining improved surface quality or for economic machining.

Table 4. Confirmation test

Level	AHP weights			Equal weights			Entropy weights		
	Initial	Prediction	Experimental	Initial	Prediction	Experimental	Initial	Prediction	Experimental
	1Mole /litter 14Volts-2Amps	3Mole-14Volts-2Amps	3Mole-14Volts-2Amps	1Mole /litter 14Volts-2Amps	3 Moles /litter 18 Volts 3 Amps	3 Moles /litter 18 Volts 3 Amps	1Mole /litter 14Volts-2Amps	3 Moles /litter 18 Volts 3 Amps	3 Moles /litter 18 Volts 3 Amps
SEC x 10^5 (J/cm^2)	5.873	-	5.577	5.873	-	8.327	5.873	-	8.327
ROC (μm)	50.556	-	50.5668	50.556	-	50.589	50.556	-	50.589
MRR (mg/min)	0.029	-	0.033	0.029	-	0.057	0.029	-	0.057
CC	0.8629	0.9405	0.8909	0.43836	0.67041	0.68109	0.42938	0.675691	0.68677
% difference		5.31%			1.47 %			1.49 %	
% improvement in CC		3.14 %			35.63 %			37.47 %	

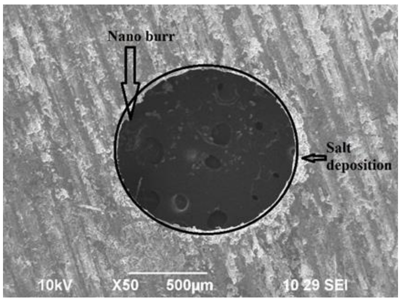

Figure 6. Micrograph of drilled hole (3 molar-18 Volts-3 Amps)

4. Conclusions

The application the various weighting schemes integrated with TOPSIS method was described for optimizing the process governing parameters during sustainable electrochemical drilling of AA6061-TiB_2 composites. From the experimental investigation, the following notable conclusions were reached.

The TOPSIS method effectively ranked the various experimental trials and identified the optimal levels of process governing parameters as 3 molar electrolyte concentration, 18 V applied voltage, and 3 A current, for sustainable machining. The entropy method outperformed equal weights and gave a larger improvement in closeness coefficient from the initial parametric settings. The sustainability aspect of machining was not relying upon the SEC. Entropy weighting facilitated assessing the role of SEC and how this response is interlinked with overcut and rate of material removal. Analysis of the results showed that entropy weighting integrated with TOPSIS method improved the ECM efficiency within the sustainable framework, as expected in the current manufacturing scenario. Furthermore, this method could be used to optimize any machining process with multiple responses by varying the weights of responses based on the objective function.

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