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A simple and reliable multi-objective optimization for tracing optimal EDM parameters to realize the leaf-shape micro-channel AA6061 heat sink

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Abstract

High performance circuits in electronic systems dissipate huge amount of heat. Efficient cooling is required to prevent such overheating. Simple and compact heat sinks can maximize convection for cooling machines and electronics. It is essential to adopt appropriate designs for cost minimization and cooling maximization. For metal removal, EDM uses a pulsating electrical charge of high-frequency current transferred from an electrode to the work-piece. It works well for finishing. This paper presents the optimal EDM parameters to realize the leaf-shape micro-channel AA 6061 heat sink by characterizing the surface finish. Current, pulse on time, and pulse off time are the EDM adjustments. Material removal rate (MRR) and surface roughness (SR) are the performance indicators. The three EDM parameters are organised in an orthogonal array according to Taguchi's method. The best EDM settings for achieving maximum MRR are shown to be distinct from the settings for achieving lowest surface roughness. The ideal EDM parameters for maximising MRR and minimising SR are determined using a straightforward and trustworthy multi-objective technique that takes into account the needs of the process designer. The MRR and SR are empirically derived as a function of the parameters of the EDM. The ranges of the estimated and tested values are quite similar.

Keywords: ANOVA; Current; Material removal rate (MRR); Multi-objective optimization; Pulse-on-time; Pulse-off-time; Surface roughness (SR).

1. Introduction

The micro-channel heat sink is an efficient and space-saving method of dispersing heat from electronic components [1]. To cool the machine, heat sinks are utilized to its hot parts (https://www.cdn-inc.com/heatsinks/). Cost minimization and cooling maximization of heat sinks demand appropriate design considerations. Aluminium is mechanically well suited for heat sinks, which has a better conductor of electricity. To have product life with efficiency, access for cleaning should be provided to protect heat sinks from clogging debris (such as dust, loose fibres or hair). Various micro-channel configurations have been proposed to fulfil the demands on cooling of the electronic devices [2-4]. EDM, or electrical discharge machining, is a technique used to cut through metal. Electric spark erosion is used here for metal removal. High-frequency electrical current is pulsed via an electrode and applied to the work-piece. EDM works well for finishing of hard materials and complicated geometries. It is possible to machine conductive metals, delicate, intricate parts (https://fathommfg.com/edm-surface-finishing). Raghuraman et al. [5] have used Taguchi and grey rational analysis to find the optimal values of current, pulse-on time, and pulse-off time for electrical discharge machining (EDM) of mild steel IS2026. These values were determined by analyzing three performance indicators: surface roughness (SR), tool wear rate (TWR), and material removal rate (MRR). Nanoparticle mixed electrical discharge machining (NPMEDM) was performed on INCONEL718 by Bhoopathy and Sundaram [6] using a brass electrode, and the effects of titanium carbide nanoparticle mixed dielectric fluid, pulse-on-time, pulse-off-time, and current on MRR and TWR were studied. The MRR has increased while the TWR has decreased. Modi et al. [7] have made a review on the EDM process and recommended cheaper air hardening tool steel as a forming tool for low duty cutting application. They suggested using Taguchi's DOE and RSM to optimise machining parameters including pulse-off-time, pulse-on-time, and servo voltage to boost MRR and surface finish. Raghav et al. [8] have conducted a statistical regression study to establish connections between the variables of the EDM process and the performance indicators that will serve as the goals functions for optimisation with the use of generic GAs. The results are confirmed with test data on MRR in EDM using mild steel. They claimed that this methodology can be applied to complex mechanical engineering problems. According to Taguchi's DOE, Bahgat et al. [9] tested the impact of the electrode material, pulse-on-time, and peak current on the machining of H13 die steel. With respect to quality and expense, the MRR, SR, and electrode wear rate (EWR) are the process efficiency metrics. Minitab 17 is used to analyse the test results. The MRR and EWR are both improved by using a copper electrode, whereas the SR is improved by using a brass electrode. For the machining of a leaf-shaped microchannel AA6061 heat sink, Mohite and Gaikwad [10] have looked at how EDM process factors like current, pulse-on-time, and pulse-off-time affect MRR and SR. The test data is generated using Taguchi's (Orthogonal Array) technique. The effect of EDM settings on performance indicators (MRR and SR) is studied by doing an analysis of variance (ANOVA) on transformed test data with a signal-to-noise (S/N) ratio of 4.0. While the transformations in Refs. [5-10] each only apply to a single set of test data, Taguchi offered the notion of altering the signal-to-noise (S/N) ratio to account for variance between repeated tests, providing a single value of the output response [11].

Fewer tests are recommended by the Taguchi method [11] for OA. Using analysis of variance (ANOVA) on the test results, the optimum process parameters on the IPIs will be determined. Results will be confirmed by further testing if deemed necessary. Successful applications of the approach (without S/N ratio modification) include the mitigation of drilling-induced damages in composites [12], among others, the satellite separation process [13], performance of heat exchangers [14, 15], planetary gears design [16] and other manufacturing processes [17-24].

In order to realise the leaf-shaped micro-channel AA 6061 heat sink, this work proposes the best EDM parameters (namely, Current, pulse-on-time, and pulse-off-time) by characterising the surface quality. Each of the three EDM parameters is given a value from 0 to 3 using Taguchi's method. A straightforward and trustworthy multi-objective technique is utilised to trace a set of optimum EDM parameters that will allow for maximum MRR and minimal SR, as specified by the process designer. The range of uncertainty for the test data is determined to be within the range of uncertainty for the empirical relations that were constructed.

2. Test data acquisition

Mohite and Gaikwad [10] We settled on AA6061a, a micro-channel heat sink material, for the piece and copper, a traditional metal for electrodes, for the tool. AA6061 has good heat absorption ability and also possesses good surface finish. The properties of tool electrode copper material are: Melting point, T_m =1083°C; Elastic modulus, *E*= 123 GPa; Poisson's ratio, $\nu = 0.26$; and density $\rho = 8.9\ gm/cm^3$. They have developed the electrode as per the design of leaf shape micro-channel. The EDM machine (Specifications: ELECTRONICA model; 2kW power consumption; Electro mechanical servo system; 30A discharge current; 75V supply voltage) was used for the machining. The voltage of the machine's pulses is constant. The discharge current, on-time, and off-time are all taken into account as parameters of the EDM process. Workpiece weights before and after processing are used to determine the material removal rate (MRR). $(W_i\ and\ W_f)$, machining time (t) and density (ρ) from

$$\text{MRR}=\frac{(W_i - W_f)}{\rho t} \tag{1}$$

Roughness (SR) may be evaluated using a surface roughness tester. When calculating SR, the cutoff length is used in conjunction with a comparison of the high and low points to the mean line. The number of experiments and the levels at which EDM process variables are set are linked in the Taguchi method. (N_{Taguchi}) as [11]

$$N_{\text{Taguchi}} = 1 + n_p \times (n_l - 1) \tag{2}$$

To account for all possible permutations of three EDM process variables () and three levels (), the designer must perform 27 (i.e., $n_l^{n_p} = 3^3$) tests, whereas equation (2) gives N_{Taguchi} = 7. Taguchi method recommends $L_9\,OA$ recording the test data for MRR and SR.

3. ANOVA

Discharge current, pulse-on time, and pulse-off time are the three EDM process variables that have been arbitrarily labelled A, B, and C for ease of reference. Test results for MRR (mm3/min) and SR () are shown in Table-1 [10]. Given NTaguchi=9 and 3, equation (2) yields in this instance. Table-1 includes a made-up parameter, D, in the same vein as [18]. ANOVA tests are taken. It is observed that C has the most impact on MRR, contributing 57.7%, and that A has the greatest impact on SR, contributing 85.4%. A and B's respective contributions to MRR are 39.7 and 0.9%. B and C's respective SR contributions are 0.3% and 10.7%. The combined MRR and SR %Contribution from elements A, B, C, and D equals 100. Therefore, given D, Error (percent) = 0. Error (percent) = %Contribution of D if D is not present.

Table- 1: EDM process variables with assigned levels and measured performance indicators.

(a) (a) Parameterization of machining, including level specifications

Machining parameters	Designation	Level-1	Level-2	Level-3
Discharge Current (Amp)	A	2	3	4
Pulse-on-time (μs)	B	30	50	90
Pulse-off-time (μs)	C	5	7	9
Fictitious		d_1	d_2	d_3

(b) Performance indicators

Test Run	Parameters and levels				Test [10]	
	A	B	C	D	MRR (mm^3/min)	a (µm)
1	1	1	1	1	1.05E-02	1
2	1	2	2	2	8.50E-03	1.01
3	1	3	3	3	8.20E-03	0.955
4	2	1	2	3	1.05E-02	1.025
5	2	2	3	1	1.02E-02	0.995
6	2	3	1	2	1.38E-02	1.04
7	3	1	3	2	1.05E-02	1.085
8	3	2	1	3	1.40E-02	1.09
9	3	3	2	1	1.05E-02	1.1

Table-2: Analysis of variance findings demonstrating the importance of EDM process factors.

Machining parameters	1-Mean	2- Mean	3-Mean	SOS (Sum of Squares)	%Contribution
Material Removal Rate (MRR): grand mean = 1.074E-02 mm^3/min					
A	9.067E-03	1.150E-02	**1.167E-02**	1.271E-05	39.7
B	1.050E-02	**1.090E-02**	1.083E-02	2.756E-07	0.9
C	**1.277E-02**	9.833E-03	9.633E-03	1.846E-05	57.7
D	1.040E-02	1.093E-02	1.090E-02	5.356E-07	1.7
Surface Roughness (SR): grand mean= 1.0333 μm					
A	**0.9883**	1.0200	1.0917	1.68E-02	85.4
B	1.0367	**1.0317**	1.0317	5.00E-05	0.3
C	1.0433	1.0450	**1.0117**	2.12E-03	10.7
D	1.0317	1.0450	1.0233	7.17E-04	3.6

4. Estimated range of MRR and SR

The process designer has to know the variation in MRR and SR. Estimates for the provided levels of the EDM process variables may be calculated by using the additive law [11] and the notation as the output response (either MRR or SR).

$$\hat{\phi} = \bar{\phi}_g + \sum_{i=1}^{n_p}\left(\bar{\phi}_i - \bar{\phi}_g\right) = \sum_{i=1}^{n_p}\bar{\phi}_i - \left(n_p - 1\right)\bar{\phi}_g \qquad (3)$$

Here $\bar{\phi}_g$ is the overall average ϕ from all the simulations; and here $\bar{\phi}_i$ is the average from the ϕ ANOVA table for the EDM parameters at the level you chose. In this case, the subscripts represent the letters A, B, C, and D. Table-3 shows that the 9 test runs of the Taguchi orthogonal array are similar with test data for both the MRR and SR estimates.

Table-3: Estimates of MRR and SR.

Test Run	Machining parameters				Test [*]	Estimate Eq. (3)			Estimated range	
	A	B	C	D		$n_p = 3$	R.E. (%)	$n_p = 4$	Min.	Max.
Material Removal Rate, MRR (mm^3/sec)										
1	1	1	1	1	1.05E-02	1.08E-02	-3.3	1.05E-02	1.05E-02	1.10E-02
2	1	2	2	2	8.50E-03	8.31E-03	2.2	8.50E-03	7.97E-03	8.50E-03
3	1	3	3	3	8.20E-03	8.04E-03	1.9	8.20E-03	7.70E-03	8.23E-03
4	2	1	2	3	1.05E-02	1.03E-02	1.5	1.05E-02	1.00E-02	1.05E-02
5	2	2	3	1	1.02E-02	1.05E-02	-3.4	1.02E-02	1.02E-02	1.07E-02
6	2	3	1	2	1.38E-02	1.36E-02	1.4	1.38E-02	1.33E-02	1.38E-02
7	3	1	3	2	1.05E-02	1.03E-02	1.8	1.05E-02	9.97E-03	1.05E-02
8	3	2	1	3	1.40E-02	1.38E-02	1.1	1.40E-02	1.35E-02	1.40E-02
9	3	3	2	1	1.05E-02	1.08E-02	-3.3	1.05E-02	1.05E-02	1.10E-02
Surface Roughness, Ra (μm)										
1	1	1	1	1	1	1.0017	-0.2	1	0.992	1.014
2	1	2	2	2	1.01	0.9983	1.2	1.01	0.988	1.010
3	1	3	3	3	0.955	0.965	-1.0	0.955	0.955	0.977
4	2	1	2	3	1.025	1.035	-1.0	1.025	1.025	1.047
5	2	2	3	1	0.995	0.9967	-0.2	0.995	0.987	1.009
6	2	3	1	2	1.04	1.0283	1.1	1.04	1.018	1.040
7	3	1	3	2	1.085	1.0733	1.1	1.085	1.063	1.085
8	3	2	1	3	1.09	1.1	-0.9	1.09	1.090	1.112
9	3	3	2	1	1.1	1.1017	-0.2	1.1	1.092	1.114

For instance, in Eq. (3), gives MRR and SR estimates without D, and corresponds to the case of estimates with D. D yields estimates that are quite similar to the true data. The estimate interval may be calculated using equation (3), which takes into account just the lowest and maximum mean values of MRR and SR for D. Estimates of MRR are adjusted by -3.444E-04 and 1.899E-04 mm3/min, respectively, for the levels of A, B, and C of the EDM process variables. Similarly, the SR estimate adjustments are -0.01 and 0.012 m, respectively. Table 3's test results are within the predicted ranges for MRR and SR. The Taguchi method recommends a small sample size of 9. The MRR and SR estimations for all 27 potential combinations of EDM process variables are given by the additive rule [11] in Equation (3) (see Figures 1 and 2). Sequential ordering of all 27 possible permutations of EDM process variables yields. Numbers 1, 5, 9, 11, 15, 16, 21, 22, and 26 correspond to the 9 trials used to generate Table-1's Taguchi's L9 OA. Test findings of MRR and SR in Table-1 are within/close-to the lower and upper limit estimations in Figures 1 and 2.

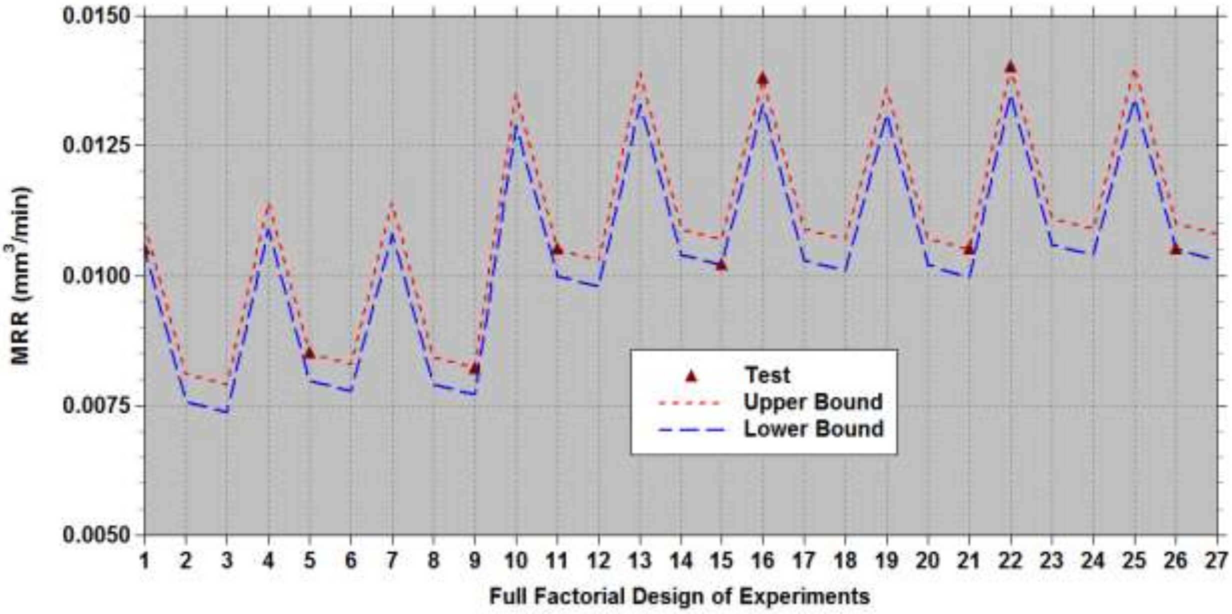

Figure-1: Comparison of test results [10] with MRR estimates.

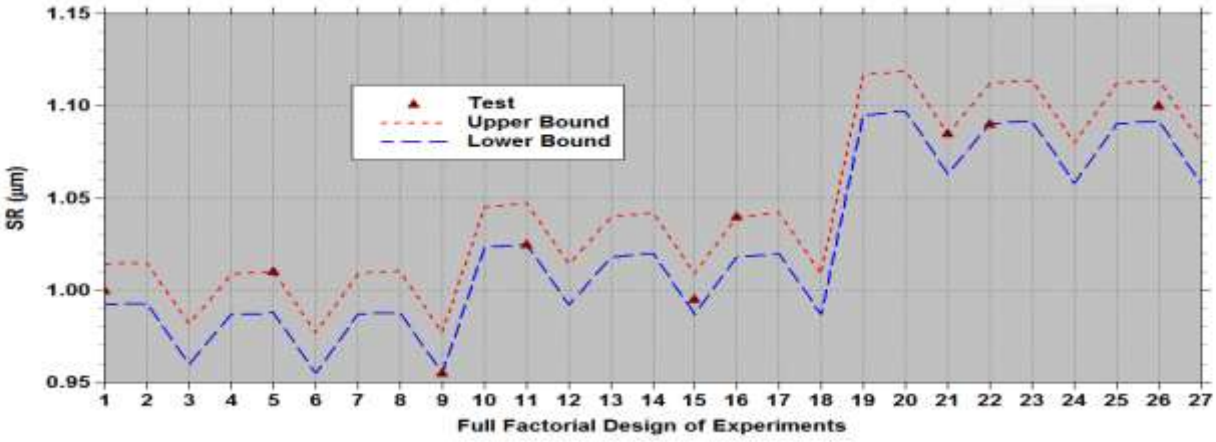

Figure-2: Comparison of test results [10] with SR estimates.

5. Growing Empirical Connections

Using the means from ANOVA Table-2, we derive an empirical connection between MRR and Ra in terms of A, B, and C.

$$MRR = 10^{-2}(1.074 + 0.13\xi_1 - 0.1133\xi_1^2 + 0.01667\xi_2 - 0.02333\xi_2^2 - 0.1567\xi_3 + 0.1367\xi_3^2) \quad (4)$$

$$SR = 1.03 + 0.05167\xi_1 + 0.02\xi_1^2 - 0.0025\xi_2 + 0.0025\xi_2^2 - 0.01583\xi_3 - 0.0175\xi_3^2 \quad (5)$$

Here, $\xi_1 = A - 3$; $\xi_2 = \frac{(B-50)(150-B)}{2400}$; and $\xi_3 = \frac{1}{2}(C-7)$.

Lower limit values of MRR and SR may be obtained by adjusting equations (4) and (5) by -3.444E-04 mm3/min and -0.01 m, respectively. Corrections of 1.889E-04 mm3/min and 0.012 m are applied to MRR and SR in equations (4) and (5), respectively, to yield upper limit values of MRR and SR. Figures 3 and 4 provide a useful comparison of MRR and SR estimations based on the additive rule (3) and the derived relations (4) and (5). The mean values plots of MRR and SR are used to derive the quadratic character of empirical relations (4) and (5). The solutions in equations (4) and (5) are comparable to those in equation (3), which is the additive law.

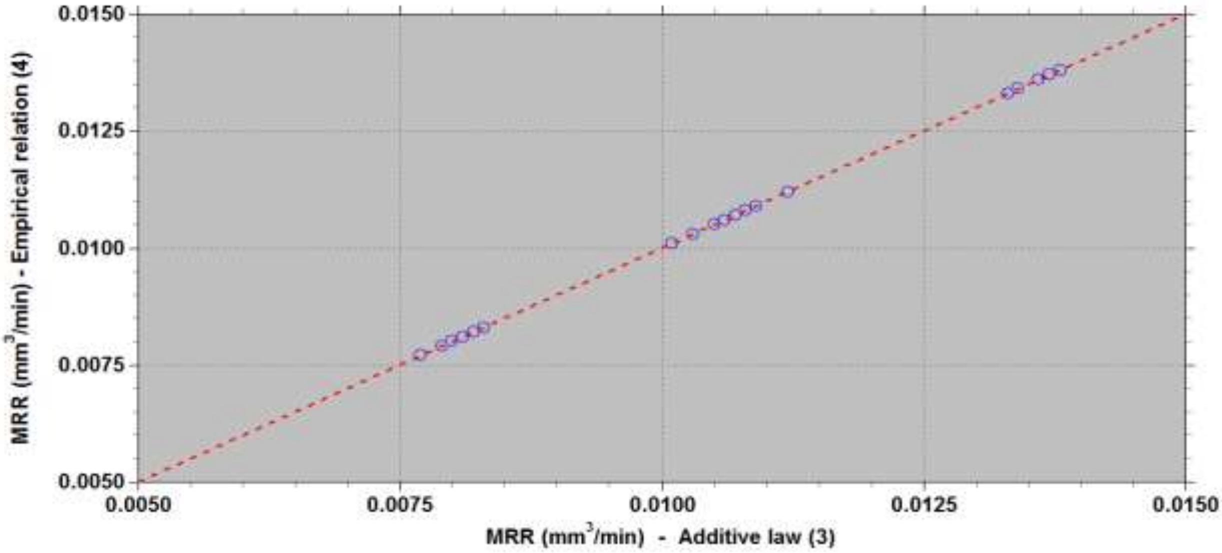

Figure-3: Comparison of MRR estimates.

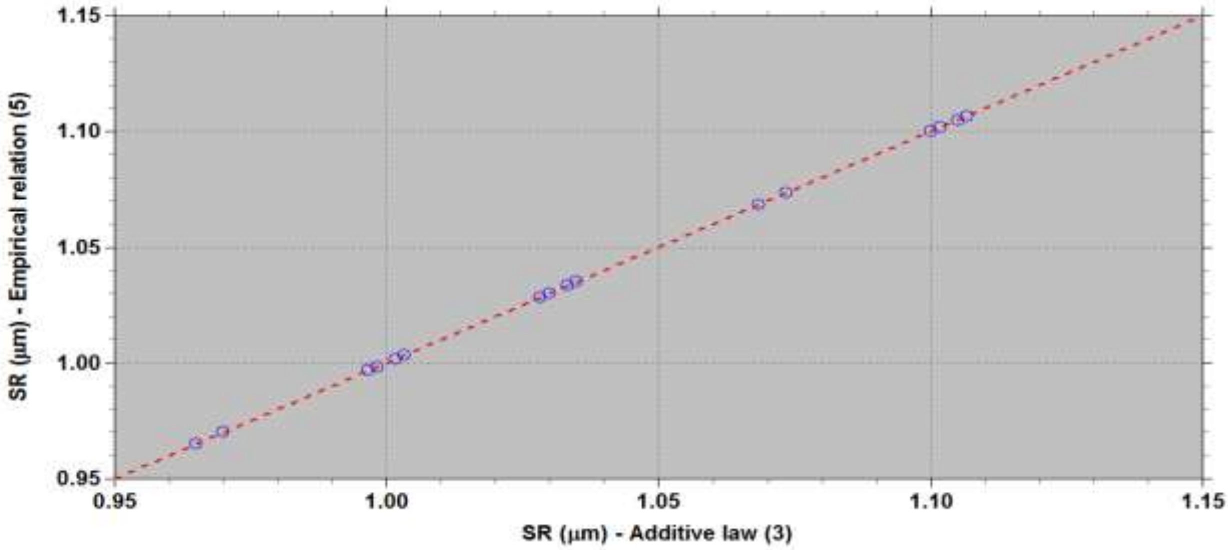

Figure-4: Comparison of SR estimates.

6. Optimal Solution

For maximum MRR, one may use the EDM parameters listed in ANOVA Table-2 (where subscripts indicate parameter levels), whereas the corresponding values for minimal SR are. It's important to note that the maximum MRR and minimum SR sets are distinct. The current multi-objective functions (MRR and SR) are changed to a single objective function as in [21-23] so that we may use the same set of EDM parameters to maximise MRR and minimise SR. Table 2 of the ANOVA results displays MRR and SR that have been normalised by their maximum values. $(MRR)_{\max}$ = 1.4033E-02 mm^3/min; and $(SR)_{\max}$ = 1.11833 µm. Defining $\zeta_1\left(\equiv 1-\frac{MRR}{(MRR)_{\max}}\right)$ and $\zeta_2\left(\equiv \frac{SR}{(SR)_{\max}}\right)$, To maximise MRR and minimise SR, one has to discover the minimal value for ζ_1 and ζ_2 . To maximise MRR while minimising SR, a single objective function i (ζ) s formulated by specifying the positive ω_1 and ω_2 and weighting elements (which fulfil $\omega_1+\omega_2=1$) as in [21–23].

$$\zeta=\omega_1\zeta_1+\omega_2\zeta_2 \tag{6}$$

Maximum MRR and minimal SR are achieved by minimising a single objective function (ζ) associated with the EDM. Minimising for ω_1=1 ($\Rightarrow \omega_2$ =0), maximises MRR with.

Minimising results in the lowest SR with for $A_1B_2C_3$. ANOVA Table-2 highlights these two instances with bolded numbers. There are two criteria (ω_1 and ω_2) that need to be considered while deciding on the optimal process conditions for a certain use case.

Normalised MRR values are $(MRR)_{\max}$ = 1.4033E-02 mm^3/min; and normalised SR values are $(SR)_{\max}$ = 1.11833 µm in ANOVA Table-2. The averages of and are ζ_1 and ζ_2 calculated. Equation (6) yields a single goal function (ζ) by multiplying the average values ζ_1 and ζ_2 of and by equal weighting factors (and). Maximum MRR and minimal SR may be achieved using the following set of parameters $A_2B_2C_1$, which was determined by finding the minimum mean values ζ of these variables (Table-4). Table 5 provides estimates of MRR and SR in addition to EDM parameters for a variety of circumstances.

Table-4: Standard deviations of a single criterion (ζ) in Equation (6) with varying scales of importance (ω_1 and ω_2).

EDM Parameters	1-Mean	2-Mean	3-Mean	Optimal Solution
$(MRR)_{\max}: \omega_1 = 1 \; and \; \omega_2 = 0$				
A	0.3539	0.1805	**0.1686**	$A_3B_2C_1$
B	0.2518	**0.2233**	0.2280	
C	**0.0902**	0.2993	0.3135	
$(SR)_{\min}: \omega_1 = 0 \; and \; \omega_2 = 1$				
A	**0.8838**	0.9121	0.9762	$A_1B_2C_3$
B	0.9270	**0.9225**	0.9225	
C	0.9329	0.9344	**0.9046**	
$(MRR)_{\max}$ and $(SR)_{\min}: \omega_1 = \frac{1}{2} \; and \; \omega_2 = \frac{1}{2}$				
A	0.6188	**0.5463**	0.5724	$A_2B_2C_1$
	0.5894	**0.5729**	0.5753	
	0.5116	0.6168	0.6091	

Table-5: Parameters of the EDM and estimated MRR and SR for a given set of circumstances.

EDM Parameters				Material Removal Rate, MRR (mm^3/min)	Surface Roughness, SR (µm)
Optimal Set	Discharge current, A (Amp)	Pulse-on-time, B (μs)	Pulse-off-time, C (μs)		
Single objective optimization - $(MRR)_{\max}$					
$A_3B_2C_1$		0		0.0135 – 0.0140 (0.0140)$^+$	1.090 – 1.112 (1.09)
Single objective optimization - $(SR)_{\min}$					
$_1B_2C_3$		0		0.00777 – 0.00830	0.955 – 0.977
Multi-objective optimization - $(MRR)_{\max}$ and $(SR)_{\min}$					
$_2B_2C_1$		0		0.0133 – 0.0139	1.018 – 1.040

Figure 5 illustrates the relationship between MRR and SR as a function of discharge current (A) for a given $B_2 = 50\,\mu s$ on and off pulse duration $C_1 = 5\,\mu s$. Material removal rate (MRR) and surface roughness (SR) are rising with the discharge current (A). For the same discharge current $A_2 = 3\,Amp$ and pulse-on time $B_2 = 50\,\mu s$, shown in Figure-6, the MRR and SR vary depending on the pulse-off time (C). The MRR and SR improve up to a 6 μs pulse-off-time (C) of 6, but then deteriorate with further increases in C. The curves in Figures 5 and 6 are generated from the developed empirical relations (4) and (5) and applying the corrections for the lower and upper bounds.

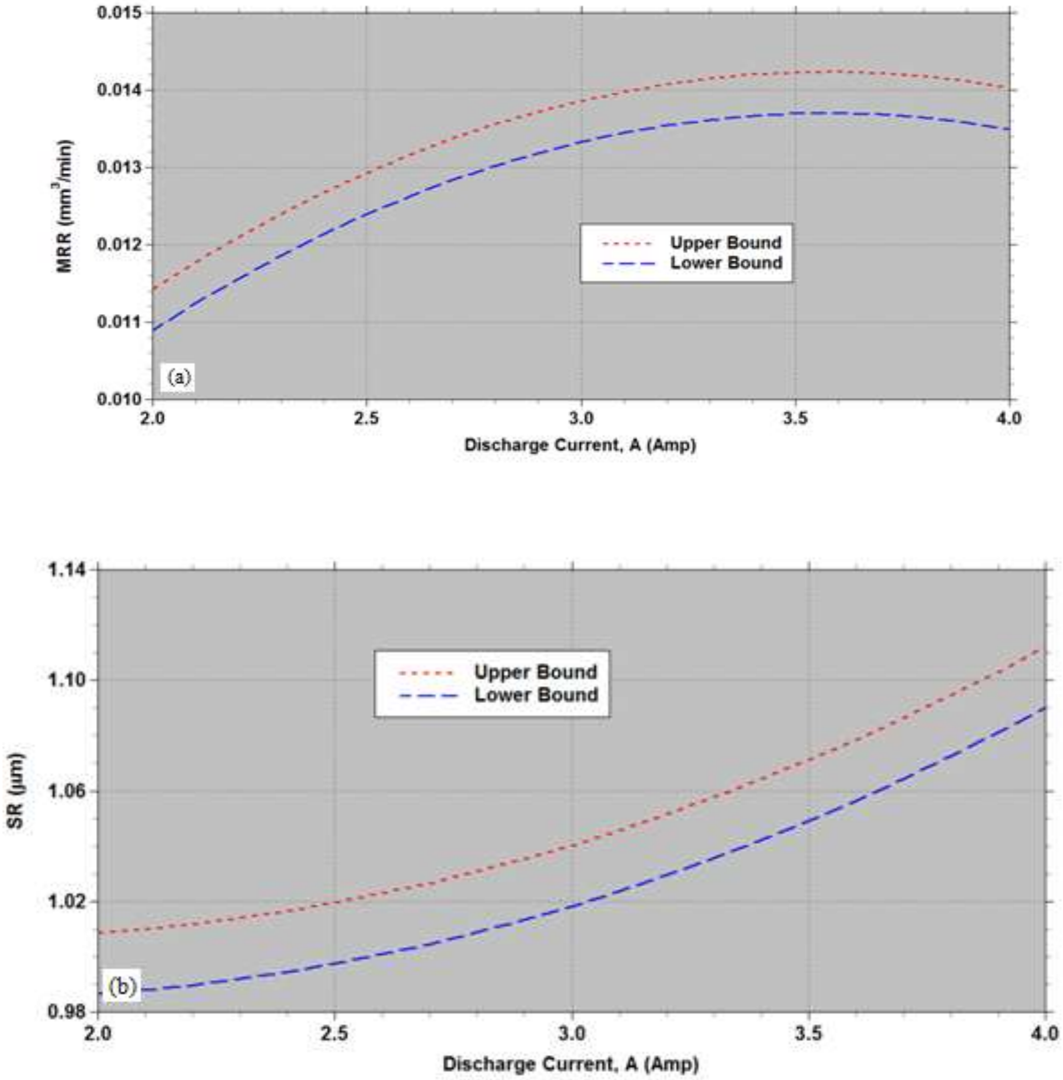

Figure-5: Variation of MRR and SR with the discharge current (A) for the specified pulse-on-time, $B_2 = 50\,\mu s$ and pulse-off-time, $C_1 = 5\,\mu s$.

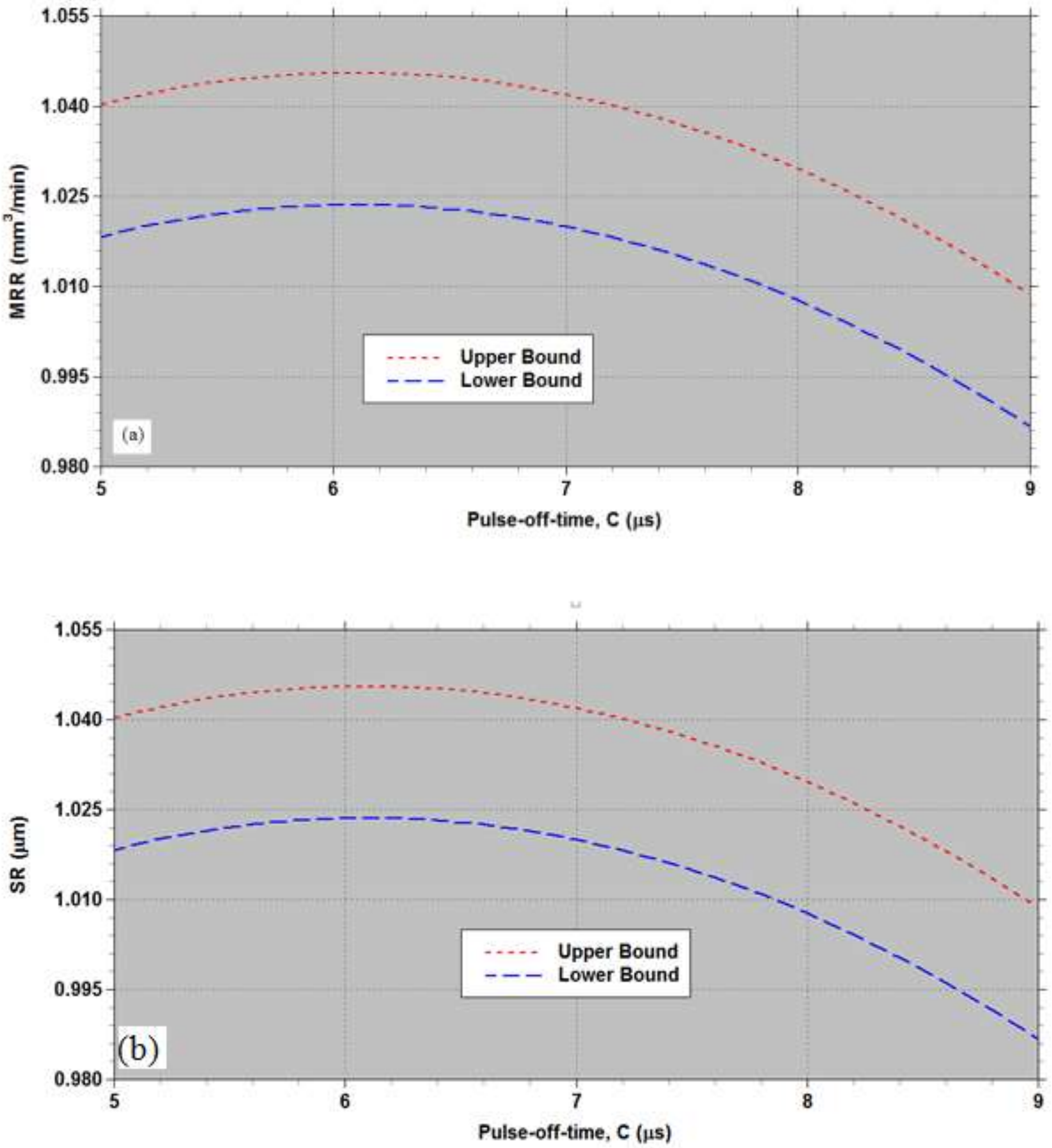

Figure-6: Variation of MRR and SR with the pulse-off-time (C) for the specified discharge current, $A_2 = 3\,Amp$ and pulse-on-time, $B_2 = 50\,\mu s$.

Concluding Remarks

To realise the leaf-shape micro-channel AA 6061 heat sink, we propose a straightforward multi-objective optimisation approach to get optimum electrical discharge machining (EDM) parameters for characterising the surface quality. The present investigation takes into account the discharge current (A), pulse-on-time (B), and pulse-off-time (C) during the EDM process. The material removal rate (MRR) and the surface roughness (SR) are markers of performance. The three variables in the EDM process are picked using Taguchi's (orthogonal array), and each variable is given three possible values. To maximise MRR and minimise SR, we determine many optimum configurations of EDM process variables. The ideal EDM settings are determined by using a multi-objective optimisation technique with the goals of maximising MRR and minimising SR. Using experimental data, we build empirical connections between MRR and SR and EDM parameters.

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