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Analysis, modeling, and optimization of hole overcut in Al-SiC metal matrix composite electrical discharge machining

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Abstract:

The accomplishment of the desired form is a fairly difficult challenge given the broad need for designed metal matrix composites, particularly in the automotive, electrical, and aviation industries. This study uses response surface methods to predictably optimise the hole overcut during electrical discharge machining of newly developed Al-SiC MMC. Under various process circumstances (flushing pressure, discharge current, pulse-on-duration, gap voltage, and pulse-off duration) produced via Box-Behnken design, machining trials are conducted. The ideal cutting solution was determined by desirability function analysis of RSM to be at 1.16 V, 11.s pulse-off time, 8.38 amp discharge current, and 0.5 kgf/cm2 flushing pressure. The actual hole overcut measured 0.2497 mm. Data on Al-SiC MMC machining would be helpful to the sector.

Keywords: Al-SiC MMC; EDM; Overcut; RSM

1. Introduction

In recent years, there has been an increase in the need for hard and brittle materials across numerous industries, particularly in the aerospace, medical device, and optical sectors. With today's technology, ensuring the required product in the most efficient manner is one of the primary challenges in manufacturing. Because to its distinct qualities (high specific strength, superior resistance to thermal distortion, wear & corrosion, and light-weight compared to standard materials), MMCs have expanded their various industrial uses in the current environment to achieve high levels of efficiency [1]. From the perspective of commercial production, standard machining techniques are incapable of producing MMC with an acceptable tolerance range. In fact, these MMCs' higher reinforcing strength and hardness make them frequently difficult to machine. Owing to highly flexible manufacturing versatility, electrical discharge machining is the most common non-traditional machining method exercised for removal of extremely hard materials effectively with complex-integrate shape in the manufacturing for miniaturization of given developments within the province of aerospace, defense, automobile, electronic, and nuclear industries. It employs a thermoelectric source of energy to machine electrically conductive parts irrespective of hardness. The process of material removal by controlled erosion via a series of pulsating electric sparks causes melting and vaporization of metal to produce almost a stress-free finished surface [2].

Despite everything, in view of the complex-dynamic performance of the EDM mechanism including its strong links in consequence of the different variables, achieving the high production efficiency from technologically-economic perspective is important. Various factors that influence the cutting phenomena during EDM are: dielectric flushes (dielectric fluids & its flushing pressure), electrode & work piece materials, electro-spark variables (voltage, discharge current, pulse duration, frequency), and others. A proper machining criterion for optimum process efficiency is still a difficult task, as modern technical approach enables significant progress in decision making. For this reason, researchers have approached various statistical [3-13] and computational [14-18] methods in their works for predictive optimization in EDM process with a view to control and to minimize the dimensional deviation machined part without compromising the surface quality.

As per with existing literature till due, only one study [1] have explored on Al-22%SiC based MMC machining via EDM. In view of machined hole overcut was not intensively highlighted in absence of surface roughness, MRR, electrode wear rate. Though, literatures related to application of response surface methodology for predictive optimization in hard turning are available in large numbers, unfortunately there has been no systematic study. In perspective to fill the research gap as stated above, this work focused on machined hole overcut during electrical discharge machining of newly engineered Al-22%SiC MMC under the influence of cutting parameters (flushing pressure, gap voltage, discharge current, pulse-off-time, pulse-on-time). Predictive optimization of hole overcut in EDM employing response surface methodology in order to improve the dimensional deviation of machined part.

2. Experimental setup and procedure

A newly engineered Al-22%SiC metal matrix composite of circular plate (size: 65mm diameter and 5 mm thickness) is chosen as work material to perform machining trials on a high accuracy electrical discharge machine (ECOWIN, MIC 432CS). Domestically available ecofriendly, bio-degradable vegetable oil and brass rod (size: diameter of 9mm) are respectively chosen as dielectric medium and electrode material during machining. During experimental trials at each parameter settings, CMM device (ZEISS MC850) embedded with a stylus probe was employed for measurement of machined hole overcut (OC). The number of machining trial were designated according to Box-Behnken design, considered based on RSM which is associated with five control factors each of having three levels namely discharge current (5, 10, 15 Amp), gap voltage (1, 1.5, 2 V), pulse-on-time (100, 200, 300 µs), pulse-off-time (10, 20, 30 µs) and flushing pressure (0.2, 0.4, 0.6 kgf/cm^2). BBD is a three levels DOE since it has no points at the vertices of the experimental domain like CCD. It might be useful if the points in the corners of a cube indicate levels that cannot be assessed or exorbitantly costly due to physical process constraints. In contrast to the popular CCD, BBD has excellent symmetry and rotatability and also develops minimum experimental execution sand provides maximum information. In this design, the treatment combinations are at the midpoints of the edges of the cube and at the centre, as shown in Figure 1. Experimental layouts results consisting of forty-six runs are presented in Table 1. Figure 2, pictorially represents the schematic layout of procedure followed for machining setup and experimental investigations.

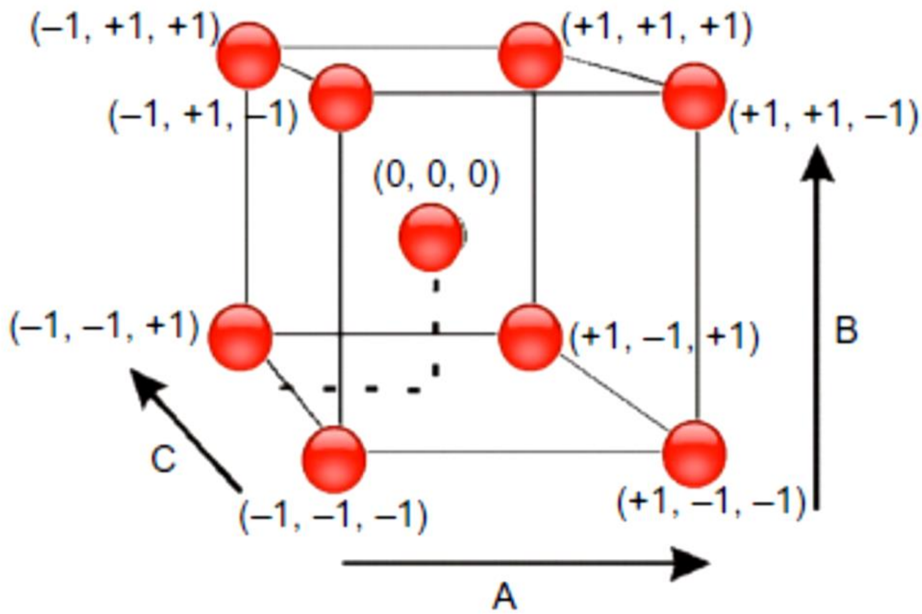

Figure1: A graphical representation of Box-Behnken design

Table 1: Experimental plan layout and results

Trial no.	Machining process parameters					Machining response
	DC (Amp)	GV (V)	T_{ON} (μs)	T_{OFF} (μs)	FP (kgf/cm^2)	OC (mm)
1	10	2	200	20	0.60	0.3102
2	10	2	300	20	0.40	0.322
3	15	1	200	20	0.40	0.3756
4	5	2	200	20	0.40	0.3578
5	10	1.5	300	20	0.60	0.3067
6	10	1.5	200	30	0.20	0.3307
7	10	1	200	10	0.40	0.2596
8	15	2	200	20	0.40	0.3542
9	10	1	100	20	0.40	0.3096
10	10	1.5	300	10	0.40	0.2726
11	10	1.5	100	30	0.40	0.2829
12	10	2	200	30	0.40	0.2894
13	10	1.5	200	20	0.40	0.2964
14	10	1.5	300	30	0.40	0.3212
15	10	1.5	100	20	0.60	0.281
16	10	1	200	20	0.60	0.3249
17	5	1.5	200	20	0.20	0.3066
18	10	1	200	20	0.20	0.3266
19	10	2	200	20	0.20	0.3297

20	15	1.5	300	20	0.40	0.3577
21	15	1.5	200	20	0.20	0.3876
22	10	1	200	30	0.40	0.389
23	10	1.5	100	10	0.40	0.2979
24	10	1	300	20	0.40	0.2745
25	10	1.5	200	20	0.40	0.3019
26	5	1	200	20	0.40	0.3203
27	15	1.5	200	20	0.60	0.3318
28	10	1.5	200	20	0.40	0.2995
29	10	1.5	200	20	0.40	0.3008
30	10	1.5	200	20	0.40	0.2984
31	5	1.5	200	30	0.40	0.3587
32	10	1.5	200	10	0.60	0.2978
33	10	1.5	100	20	0.20	0.3184
34	10	1.5	200	30	0.60	0.3097
35	5	1.5	100	20	0.40	0.3217
36	5	1.5	200	10	0.40	0.2719
37	5	1.5	200	20	0.60	0.3437
38	10	1.5	200	20	0.40	0.2984
39	15	1.5	200	10	0.40	0.3704
40	15	1.5	100	20	0.40	0.3432
41	10	1.5	300	20	0.20	0.3025
42	15	1.5	200	30	0.40	0.3579
43	10	1.5	200	10	0.20	0.312
44	10	2	100	20	0.40	0.2934
45	10	2	200	10	0.40	0.3787
46	5	1.5	300	20	0.40	0.3182

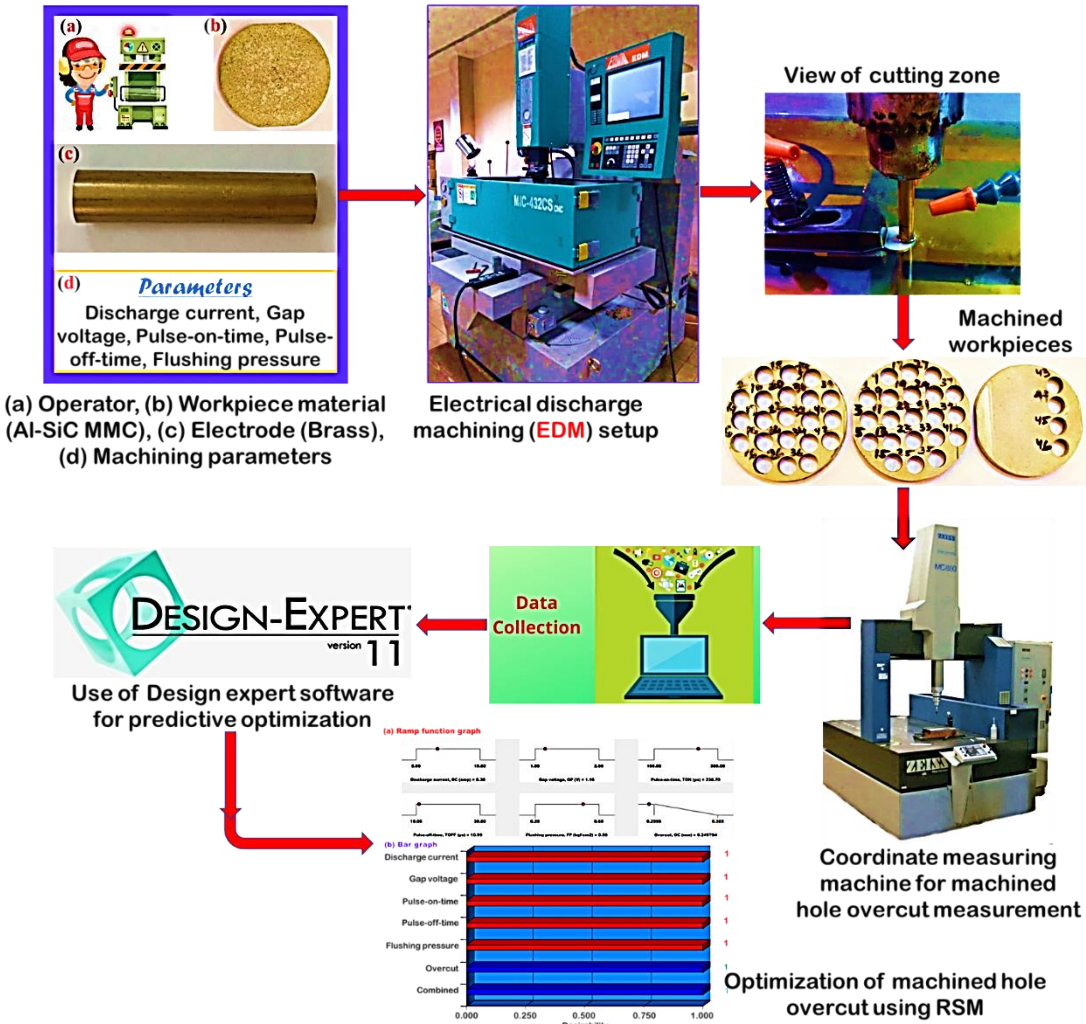

Figure 2: Schematic of machining setup and procedure for experimental investigation

2.1 Parametric analysis on machined hole overcut

The influence of machining parameters on overcut, OC was examined by employing three-dimensional surface response plot. It is evident from Figure 3 that EDM with increasing discharge current degrades surface finish for the most part which may be because of increased current density and spark energy, which clearly agrees with the previous studies. The influence of peak current contributes to increase in discharge energy per spark, and accordingly transferred considerable thermal energy to machined upper surface which in comparison to the subsurface leads to more material evaporation and consequently uneven dimensional deviations of hole leading to increasingly overcut (refer, Figure 5). The selected cutting conditions enlisting maximum geometric shape deformation of hole occurs at FP= 0.4kgf/cm^2; T_{on}= 200µs; T_{off} = 20µs; GV= 1V.Figure 4shows the SEM images of cross-section view for the side wall of machined hole formed by EDM with various discharge current. It is noticed that at lower value of DC, the side wall of machined hole generated on Al-SiC MMC is recommended than that one achieved by machining with a higher discharge current. The reason is that at lower value of DC, the current density is not so much during pulse-on-time, that resulting in less electrode (tool) wear and hence, the improved hole quality. Moreover, it is evidenced that hole taper gradually increases with the rise in discharge current from 5 to 15 amp. This may be attributed to the fact that thermal energy per unit area is more which might have resulted in high tool wear causing deterioration of tool-tip geometry. Thus, resulting geometrical deviation of hole in the form of increase hole taper.From 3D response graph for overcut, it is to be noted that OC is increasing with the increase in pulse-on-time. The reason for that the availability of energy for material removal for a specified period is participated with a smaller extent by substantial numbers of sparks at higher pulse-on time. Therefore, exploiting uneven deeper-larger crater marks at the wall edge of the machined hole (due to increased MRR) and results in increased overcut. In addition, lesser amount of metal is removed through smaller pulse-on-time and approached to better surface finish by reason of moderate thermal damage to the machined component which develops improved hole accuracy. The forced circulation of the dielectric leads tomarginal improvement in hole dimensional deviation because of decrease overcut. From Figure 4c, it was deduced that overcut decreased with flushing pressure as it avoids short circuiting and stagnation of flushing fluid during EDMing.

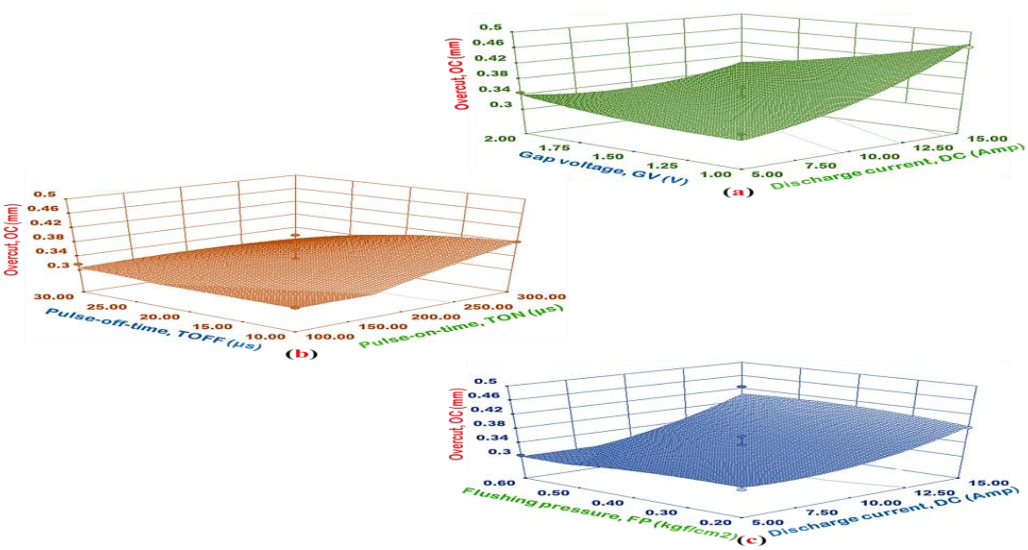

Figure 3:3-D response plot for overcut under the interaction effects of process parameters: (a) GV-DC, (b) $T_{on} - T_{off}$, (c) DC-FP

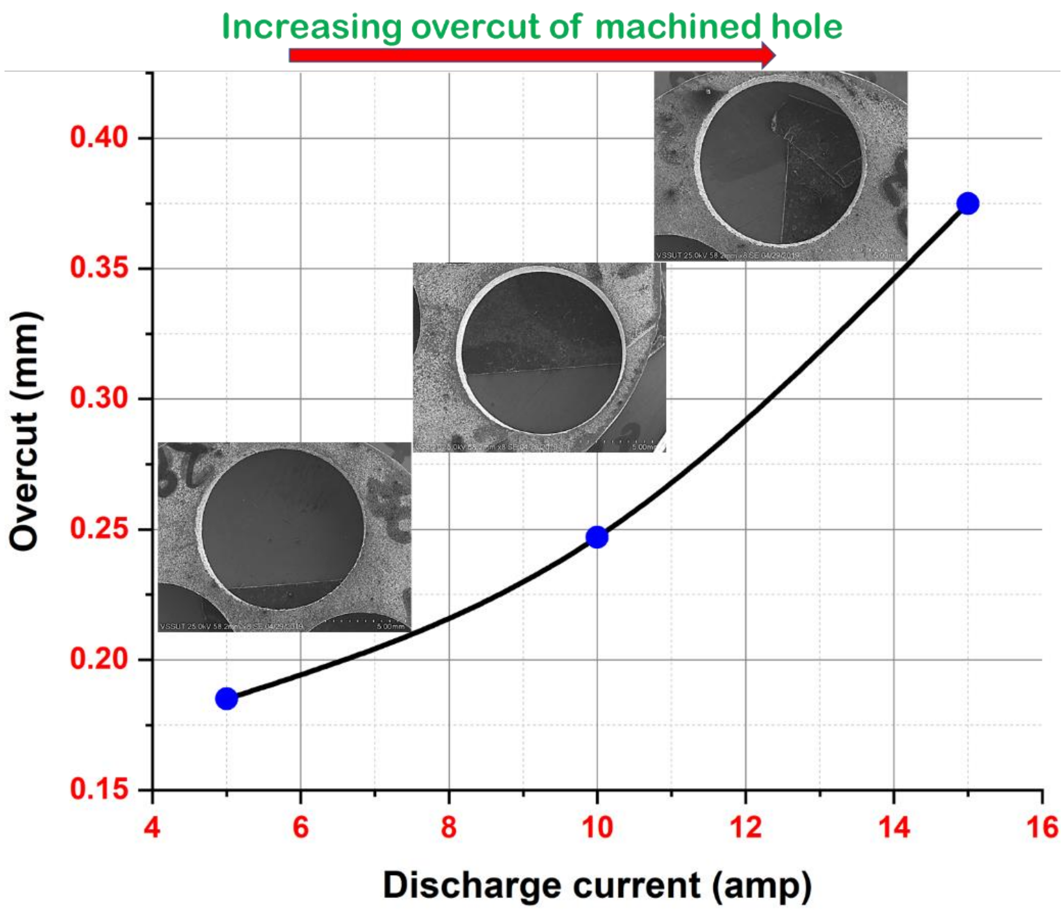

Figure 4: Dimensional deviation of EDMed hole quality under varied discharge current

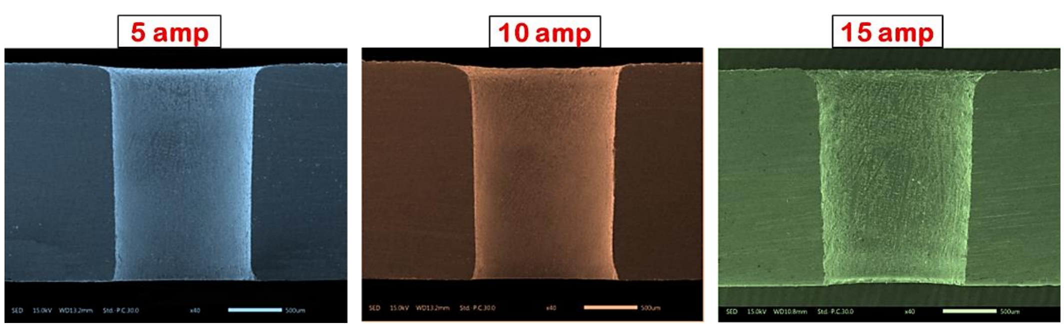

Figure 5: Effect of peak discharge current on hole quality formed by EDM at GV= 1V; TON= 200µs; TOFF= 20µs; FP= 0.4kgf/cm^2

3. Optimization using response surface methodology

Recent past, one of the best suitable technique of optimization for multi-objective and multiple responses in the metal cutting process is the desirability function analysis. Basically, it is based on multicriteria decision making. Desirability is an objective function that translates each response in the scale ranging from zero outside of the limits to one at the goal. The variables result undesirable response, if the value is 0 while the value 1 is the best performance (i.e., highly desirable) for the studied variables. After the desirability functions are established for each different response variables depending on its objectives, an overall desirability function is established, which is obtained by combining the geometric mean of distinctive desirability function. Once of the overall desirability is established, it can be used for optimal solution of predictors or responses. The Present work deals with desirability optimization methodology for minimization machined hole overcut. Such task for the predicting the optimal solution to the response (OC) was obtained using standard statistical software package Design Expert 11. For solving the optimization problem, the individual desirability function for the abovementioned output is stated as [19],

$$d_i = \begin{cases} 1 & if\ y_i \le l_i \\ \left[\frac{u_i - y_i}{u_i - l_i}\right] & if\ l_i \le y_i \le u_i \\ 0 & if\ y_i \ge u_i \end{cases} \quad \textbf{(1)}$$

Whereas, the overall desirability can be expressed as,

$$D = \left(\prod_{i=1}^{N} d_i\right) (\mathbf{2})$$

l_i and u_i are the lower and upper observation estimates of studied output. N denotes number of response variables and y_i implies predicted value for the i^{th} response.

The RSM optimization results for OC are presented in Table 2. The optimum solution having maximum desirability value (i.e., approaches to 1) was sorted out on ramp function plot, as shown in Figure 6. Optimal settings are indicated as points on each ramp graph which results in maximum desirability value. As seen from Figure 6, the optimum cutting solution is preferred at pulse-on-duration of 238.7 µs, discharge voltage of 1.16 V, pulse-off-duration of 11µs, discharge current of 8.38 Amp and flushing pressure of 0.5 kgf/cm^2. The hole overcut of value 0.2497 mm was found at the optimum parametric machining conditions.

Table 2: RSM optimization results for overcut

No.	DC	GV	T_{on}	T_{off}	FP	OC	Desirability
1	8.38	1.16	238.7	11	0.50	0.24970	1
2	7.45	1	103.64	10	0.54	0.26069	0.992
3	11.76	2	100	28.83	0.27	0.26520	0.957
4	10.55	2	134.49	30	0.27	0.27063	0.915
5	12.62	2	226.93	30	0.49	0.28074	0.839
6	10.77	1.52	100	18.60	0.6	0.28101	0.835
7	11.36	2	239.03	29.93	0.6	0.28335	0.816

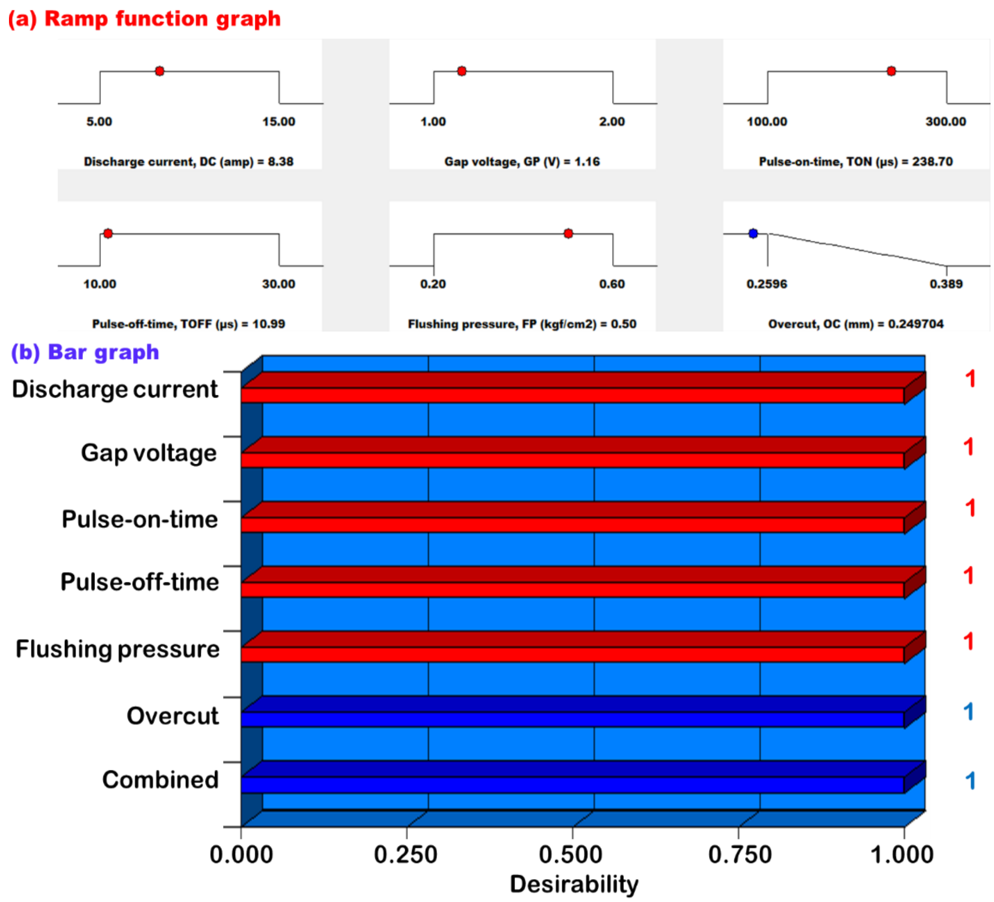

Figure 6: Optimization results using desirability function analysis

4. Conclusion

The overcut (OC) produced by EDM, or dimensional deviation of hole diameter, according to the effect plot, is caused by an increase in discharge current and pulse on time. The ideal cutting solution was determined by desirability function analysis of RSM to be at 1.16 V, 11.s pulse-off time, 8.38 Amp discharge current, and 0.5 kgf/cm^2 flushing pressure. The actual hole overcut measured 0.2497 mm. For the challenging-to-machine Al-SiC MMC, the research findings and suggested predictive design optimization will provide helpful, actionable information.

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