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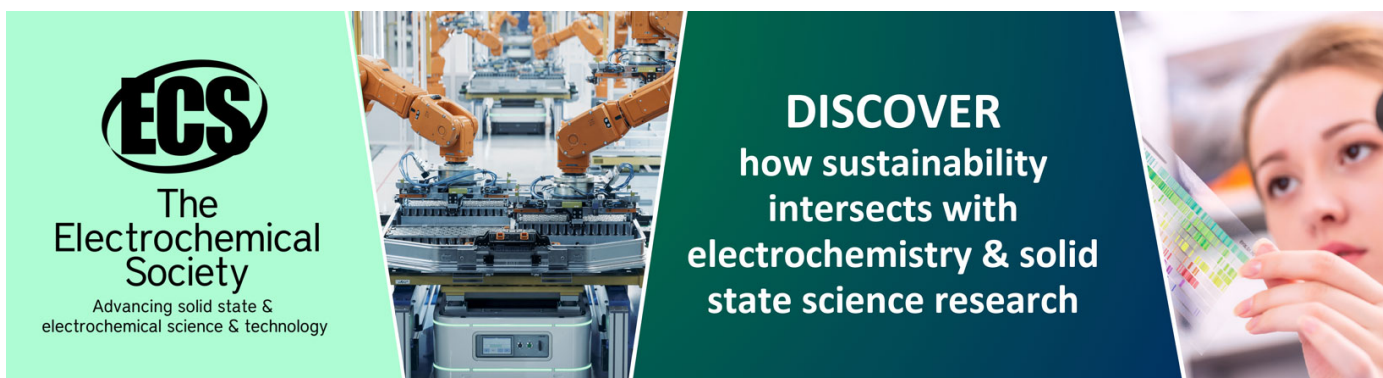
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Comparison of machining characteristics of Inconel 601 with Brass and Graphite electrode in EDM using Response Surface Methodology (RSM)

Navjyot Panpalia¹, Man Mohan Singh², Nilanjan Mandal³, *Rahul Choudhary⁴ and B C Routara⁵

^{1,2,3,4,5} School of Mechanical Engineering, KIIT Deemed to be University, Bhubaneswar, Odisha 751024, India

*Corresponding author E-mail: rahulkumar589@gmail.com

Abstract. Nickel-based super alloy (such as Inconel) is widely used in aerospace, nuclear, and chemical industries because of its excellent mechanical and chemical properties at elevated temperatures. Inconel comes under the category of “difficult-to-cut” materials. In the present case, an experimental investigation on assessing machining performance during EDM of Inconel 601 has been delineated herein. Attempt has been made on evaluating optimal machining parameters setting to achieve satisfactory machining yield. A Box–Behnken design of response surface methodology has been adopted to estimate the effect of machining parameters on the response. Experiments have been carried out by varying gap voltage, peak current, pulse-on time (each varied at three discrete levels) to examine the extent of machining performance in terms of material removal rate using Brass and Graphite electrode.

Keywords: EDM; Brass; Graphite; Inconel 601; DOE; RSM; ANOVA.

1. Introduction

In order to satisfy stringent design requirements, machining of Inconel super alloys becomes very difficult and expensive by conventional processes such as turning, milling, broaching, grinding, etc. Problems that are frequently experienced in machining super alloys by conventional techniques are rapid tool wear and excessive heat generation at the tool-work interface; thereby, results subsequent alteration of work material characteristics. As a result, manufacturers and design engineers are forced to opt for modern machining processes. EDM is an important non-conventional machining process that is commonly used in automobile, aerospace industries. The Electrical discharge machine can cut precise, complex and irregular shapes and can also cut ‘difficult to cut’ material, many miniature and micro-parts from metals, alloys, sintered materials, cemented carbides, ceramics and silicon. For EDM to work it is compulsory that both the electrode and work piece should be electrically conductive. Using EDM high degree of precision and a good surface quality can be achieved. Its working principle is based on the principle of thermoelectric energy i.e. a repetitive spark which is produced by the DC pulse generator between workpiece and tool is the main cause for the metal removal. There is a dielectric medium present in the



working environment so there is no oxide formation. Due to this discharge a large amount of heat is developed in between the tool and work-piece. This discharge causes erode the minute particles from the work –piece material and tool by melting and then get spread into the machining area which is then flushed off by the flow of the dielectric medium. The temperature at the time of metal removal may vary from 8000 degree Celsius to 12000 degree Celsius depending upon the voltage, current etc. It has many input variable like pulse ON/OFF time, voltage, current, tool polarity, flushing pressure, dielectric, electrode type, duty factor etc... The main advantage of EDM is that there is no physical contact between tool and workpiece at the time of machining.



Figure 1.EDM setup.

Here the workpiece used is Inconel 601 which is a nickel based super alloy that is used where the temperature is very high like gas turbine, nuclear reactor, high velocity gas burners, radiant tubes, refractory anchors, fabricating combustion chambers etc. It also has a high strength and is resistant to carburization. The composition of Inconel 601 is a FCC solid solution which includes nickel 59.36%, chromium 22.83%, aluminium 1.36% and density is 8.11 g/cm^3 .

Some of the important works in which machining is done through EDM on different grades of Inconel and some other difficult to cut materials with different methodology.

Bhosle and Sharma [1] developed a unique optimal parameters setting for micro-EDM drilling process using Inconel 600 alloy using GRA for MRR, taper angel, overcut. Their results concluded that capacitance has the highest influence on performance characteristics followed by voltage and feed rate played a vital role in controlling taper angel but had least influence on performance characteristics. **Lin et al. [2]** used grey-Taguchi method to optimize multi-performance characteristics like TWR and MRR during micro-milling electrical discharge machining of Inconel 718 through peak current, pulse-on time, pulse-off time, spark gap. **Routara et al. [3]** investigated Taguchi method and grey relation analysis by machining EN- 24 alloy steel in EDM with I/P parameters pulse on , pulse off, peak current and flushing pr. with observed responses MRR and TWR and they found that Taguchi's parameter design is simple, more systematic and efficient tool for maximizing the machining parameters. **Habib [4]** has analysed machining of metal matrix composite Al/SiCp with copper electrode in EDM. He analysed the effect of machining parameters such as current, gap voltage and pulse-on-time on MRR and TWR using RSM. **Rahul et al. [5]** worked on machining of Inconel 625 alloy in EDM with graphite electrode using 5-facto 4 level L_{16} orthogonal array which is carried out by using parameters which includes gap voltage, peak current, pulse on time, duty factor, flushing pressure and studied TWR, radial overcut, surface roughness, surface crack density and surface irregularities. **Sharma et al. [6]** performed WEDM of Inconel 706 and evaluated responses such as material removal rate, surface roughness, recast surface, topography, micro hardness, microstructural and metallurgical. They observed that servo voltage, pulse-on time, and pulse-off time highly affected the MRR and SR. **Mohanty et al. [7]** determined a pathway for optimum parameter setting while machining Inconel 718 in EDM. They used MOPSO algorithm and Box- Behnkin

design of RSM to collect data. In this experiment MOPSO process was found good for optimization of the responses which are MRR and surface quality. **Hewidy et al. [8]** developed mathematical models to establish interrelationship of various WEDM machining parameters of Inconel 601 by using RSM. They took into consideration peak current, duty factor, wire tension and water pr. on MRR, wear ratio and surface roughness and found that VMRR increases with peak current and water pressure and with increase in peak current wear ratio and surface roughness increases and it decreases with increase in duty factor and wire tension. **Rahul et al. [9]** worked on Inconel 601 using graphite electrode. They used 5-factor 4-level L_{16} orthogonal array methodology along with input parameters gap voltage, peak current, pulse on time, duty factor and flushing pressure. The responses include MRR, TWR, surface roughness and surface crack density. They found that the most desirable machining parameter setting as voltage=80V current=7A, pulse on time=500, duty factor=80% and flushing pressure = 0.3 bar.

From the above papers we observed that work has been done using various methodologies like Taguchi, GRA and RSM. We further saw responses like MRR, TWR, surface roughness etc. on various engineering materials which are graded as “difficult to cut” material and after thorough analysis we decided to work on Inconel 601 with brass and graphite electrode using RSM methodology with Box Behnken method.

2. Experimental Procedure

2.1. Material Used

In the present work, an alloy of nickel-chromium or Inconel 601 is taken as work piece and electrode used is brass in Figure 2 and graphite in Figure 3 with machined surfaces with respective electrodes. The dimension of work piece is 50mm x 50mm x 6mm and the brass electrode is 12 mm in diameter and graphite electrode is 12mm diameter.



Figure 2. Machined surface of Inconel 601 using Brass Electrode.

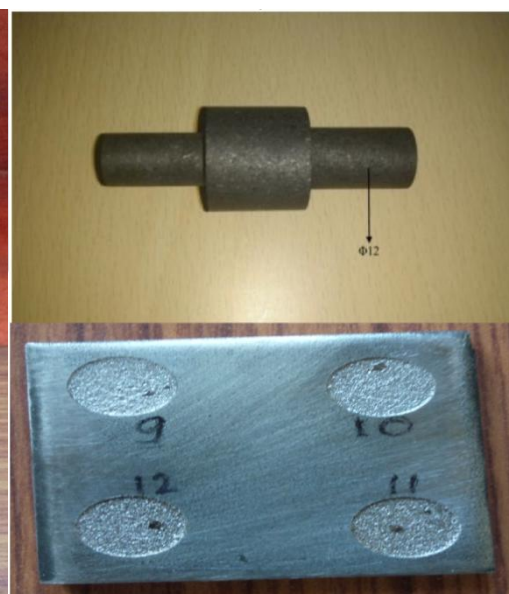


Figure 3. Machined surface of Inconel 601 using Graphite Electrode

2.2 Design of Experiment

Box-Behnken Design (BBD) is used to study the effect of process parameters in EDM given in Table 1. The experiments are carried out with three input parameters namely pulse on time (T_{on} in microsecond,

μs), peak current (I_p in Ampere, A) and gap voltage (V_g in Voltage, V). The factors with different levels are shown in Table 1 below. The results obtained with corresponding DOE is tabulated in Table 2.

Table 1. Domain of Experiments.

Factors	Name	Unit	Low Level (-1)	Medium Level (0)	High Level (1)
A	Gap Voltage	V	60	70	80
B	Peak Current	A	10	12	14
C	Pulse on time	μs	50	100	150

Inconel 601 is machined with brass and graphite electric discharge machine setup up to a depth of 0.5 mm with a constant flushing pressure of 10 kg/cm². The time for machining each work piece is recorded. Material removal rate (MRR) is calculated by the given equation (1).

$$MRR = \frac{W_i - W_f}{t} \text{ gm/min} \quad (1)$$

where,

W_i is the weight of work piece before machining (in gram),
 W_f is the weight of work piece after machining (in gram) and
 t is the machining time (in minutes).

The experimental response is shown in Table 3.

Table 2. Result (Experimental Data (MRR) Using Brass and Graphite Electrode).

S.NO.	Box-Behnken Method using RSM (DOE)			Experimental data	
	A	B	C	Inconel 601 MRR (gm/min)	
				Brass	Graphite
1	-1	-1	0	0.032223	0.083799
2	1	-1	0	0.012109	0.013825
3	-1	1	0	0.042313	0.215569
4	1	1	0	0.054759	0.059113
5	-1	0	-1	0.036675	0.138889
6	1	0	-1	0.045455	0.0625
7	-1	0	1	0.045743	0.232258
8	1	0	1	0.043426	0.070588
9	0	-1	-1	0.023622	0.092308
10	0	1	-1	0.086643	0.074534
11	0	-1	1	0.030738	0.100334
12	0	1	1	0.058366	0.197368
13	0	0	0	0.044665	0.134831
14	0	0	0	0.045831	0.145892
15	0	0	0	0.042385	0.152367

3. Results and Discussions

The result obtained through the set of experiments is to be analyzed for ensuring the fitness of model. This is done by doing a significance test. The test for goodness of fit and lack of fit is also done.

MINITAB 17 is used to analyze the experimental data and get the best possible result and analysis of variance is done to sum up the above test.

3.1. Response Surface Methodology (RSM)

Response surface methodology is a collection of mathematical and statistical technique for empirical model building. RSM is mainly used to get the optimize result for different inputs. RSM is generally used to find the significance of several input parameters on one or more output parameters.

With the help of regression analysis and design of experiment, a response for independent input parameters can be found. In RSM, the independent input parameters can be shown quantitatively by:

$$y = f(x_1, x_2, x_3, \dots, x_n) \pm \epsilon$$

where,

ϵ denote the error in response y and surface expressed by $f(x_1, x_2, \dots, x_n)$ is known as response surface.

The response can be seen by graphical method in the contour plots or by 3-dimensional space that will help to anticipate shape of response surface.

The suitability of response surface methodology is determined with the approximation of f . In first order model, lack of fit is formed due to the interactions between variables and surface curvature. To improve the optimization process second order model is used. An ordinary second order model is given by:

$$f = a_0 + \sum_{i=1}^n a_i x_i + \sum_{i=1}^n a_{ii} x_i^2 + \sum_{i < j} a_{ij} x_i x_j + \epsilon$$

where,

a_{ii} denotes the quadratic effect of x_i , a_i denotes the linear effect of x_i and a_{ij} denotes the line to line interaction between x_i and x_j and x_i and x_j are the design variables. This quadratic model allows to locate the region of optimality besides investigating entire factor space.

The important data for response surface models is collected with the help of design of experiments, with the adoption of Box-Behnken Design.

The final response equations are as follows:

$$MRR_{Brass} = 0.04429 - 0.00015V_g + 0.01792I_p - 0.00177T_{ON} - 0.00798V_g * V_g - \\ 0.00096I_p * I_p + 0.00651T_{ON} * T_{ON} + 0.00814V_g * I_p - 0.00277V_g * T_{ON} - 0.00885I_p * T_{ON}$$

$$MRR_{Graphite} = 0.14436 - 0.05806V_g + 0.03204I_p - 0.02904T_{ON} - 0.02068V_g * V_g - \\ 0.03060I_p * I_p + 0.00238T_{ON} * T_{ON} - 0.02162V_g * I_p - 0.02132V_g * T_{ON} + 0.02870I_p * T_{ON}$$

3.2. Analysis of Variance (ANOVA)

The analysis of variance for material removal rate is given in Table 4 and Table 5 for brass and graphite electrode. F-value is used to check the significance of values. The probability of F-value which exceeds the calculated F-value due to the noise is given by the P-value in the table. If P value is more than 0.05 then the term is insignificant and lacks fit. An insignificant terms is required as it indicates the left out term not significant and hence the develop model fits together. The value of coefficient of determination (R^2) and adj. R^2 are found to be 0.9732 and 0.9251 with graphite electrode and 0.9213 and 0.7796 with brass electrode respectively.

Table 3. ANOVA table for material removal rate (MRR) for Graphite electrode.

Source	DF	Adj SS	Adj MS	F -Value	P-Value
Model	9	0.05375	0.00597	20.21	0.002

		3	3		
		0.04192	0.01397		
Linear	3	8	6	47.29	0
		0.02696	0.02696		
V	1	9	9	91.25	0
		0.00821	0.00821		
I	1	2	2	27.79	0.003
		0.00674	0.00674		
TON	1	6	6	22.83	0.005
		0.00484	0.00161		
Square	3	2	4	5.46	0.049
		0.00157	0.00157		
V*V	1	9	9	5.34	0.069
		0.00345	0.00345		
I*I	1	8	8	11.7	0.019
		0.00002	0.00002		
TON*TON	1	1	1	0.07	0.801
2-Way		0.00698	0.00232		
Interaction	3	3	8	7.88	0.024
V*I	1	0.00187	0.00187	6.33	0.053
		0.00181	0.00181		
V*TON	1	8	8	6.15	0.056
		0.00329	0.00329		
I*TON	1	5	5	11.15	0.021
		0.00147	0.00029		
Error	5	8	6		
		0.00132			
Lack-of-Fit	3	1	0.00044	5.6	0.255
		0.00015	0.00007		
Pure Error	2	7	9		
		0.05523			
Total	14	1			

Table 4: ANOVA table for material removal rate (MRR) for Brass electrode.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
		0.00363	0.00040		
Model	9	1	3	6.5	0.026
		0.00259	0.00086		
Linear	3	5	5	13.95	0.007
V	1	0	0	0	0.959
I	1	0.00257	0.00257	41.43	0.001
		0.00002	0.00002		
TON	1	5	5	0.4	0.554
		0.00042	0.00014		
Square	3	6	2	2.29	0.196
		0.00023	0.00023		
V*V	1	5	5	3.79	0.109
		0.00000	0.00000		
I*I	1	3	3	0.06	0.824

			0.00015	0.00015		
TON*TON	1	7	7	2.52	0.173	
2-Way						
Interaction	3	9	3	3.27	0.117	
V*I	1	5	5	4.27	0.094	
V*TON	1	1	1	0.5	0.513	
I*TON	1	3	3	5.05	0.075	
Error	5		0.00031	2		
Lack-of-Fit	3	4	1	32.97	0.298	
Pure Error	2	6	3			
Total	14	1	0.00394			

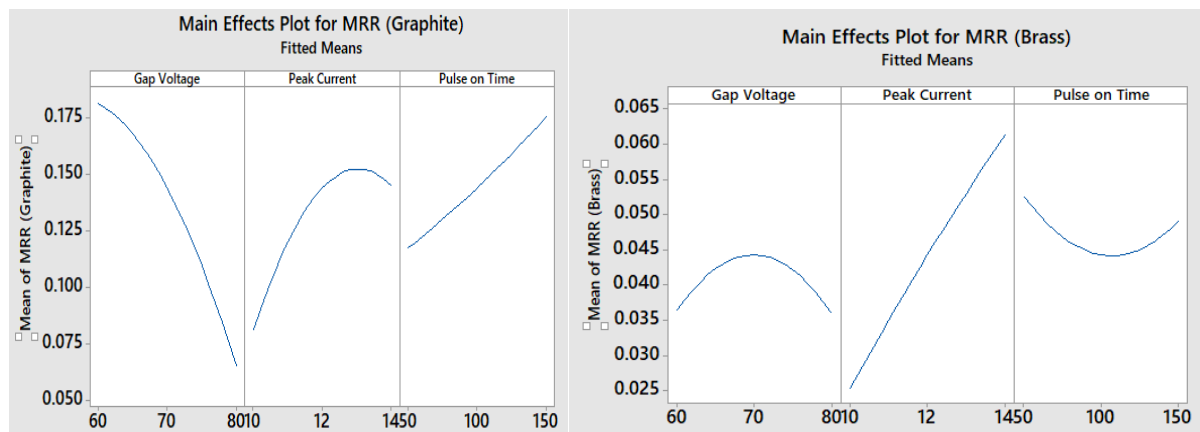


Figure 4. Main Effects Plot for MRR (Graphite and Brass)



Figure 5. MRR comparisons with brass and graphite

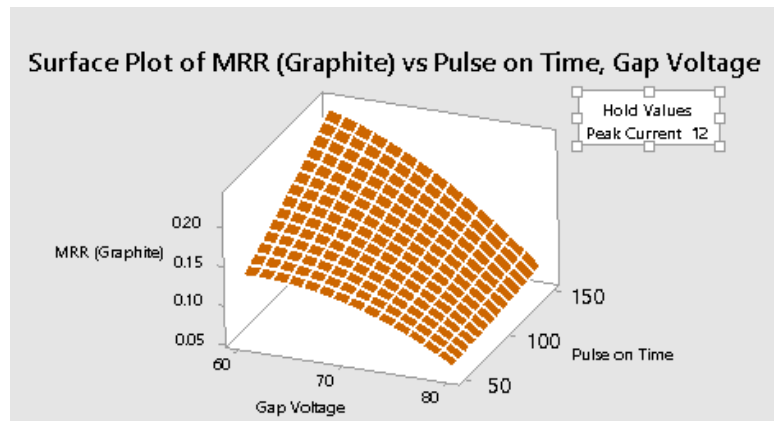


Figure 6. Surface Plot of MRR (Graphite) vs Pulse on Time, Gap Voltage

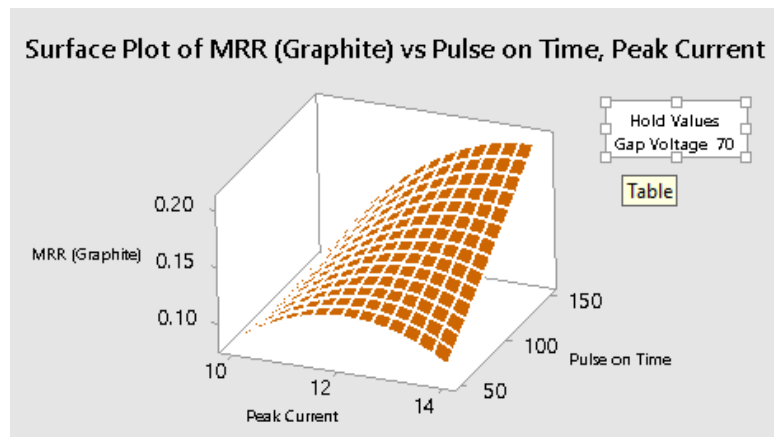


Figure 7. Surface Plot of MRR (Graphite) vs Pulse on Time, Peak Current

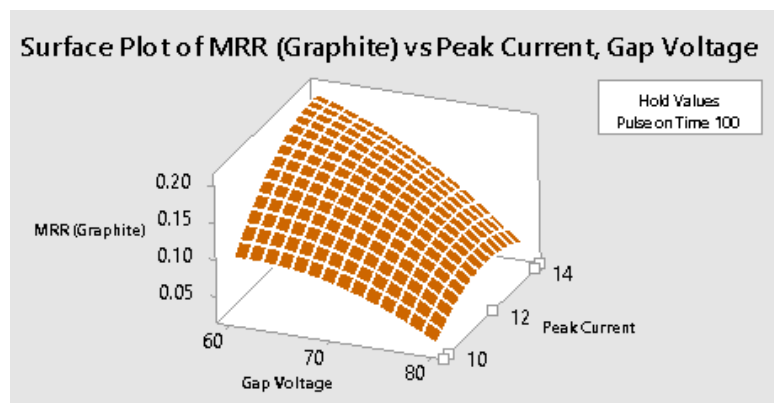


Figure 8. Surface Plot of MRR (Graphite) vs Peak Current, Gap Voltage

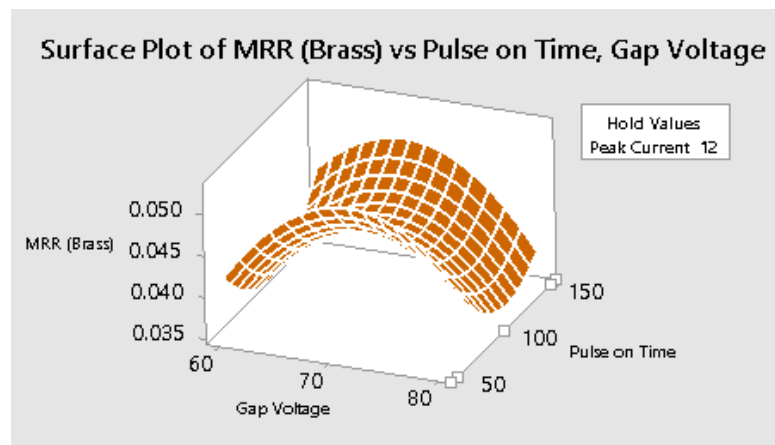


Figure 9. Surface Plot of MRR (Brass) vs Pulse on Time, Gap Voltage

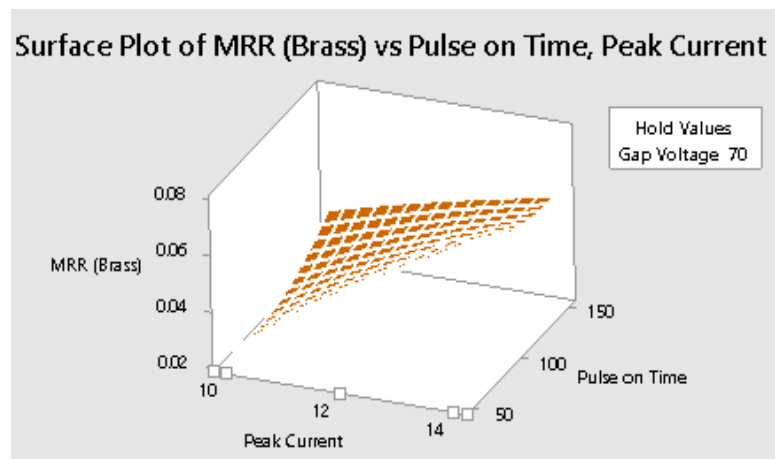


Figure 10. Surface Plot of MRR (Brass) vs Pulse on Time, Peak Current

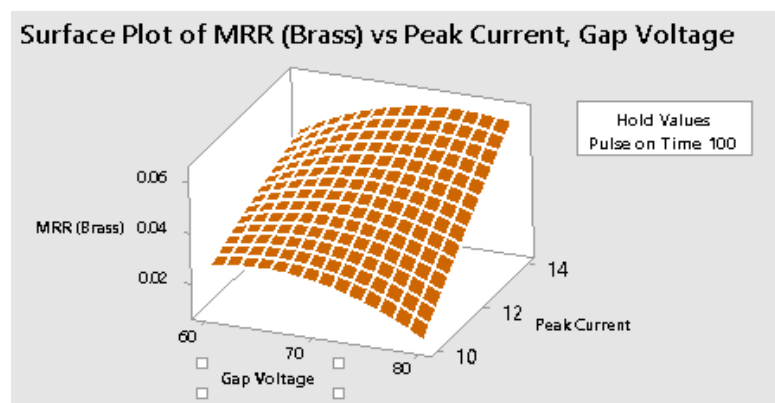


Figure 11. Surface Plot of MRR (Brass) vs Peak Current, Gap Voltage

4. Conclusion

This experimental investigation proposes a hybrid, integrated approach of response surface methodology (RSM).

1. Tool material, discharge current and pulse-on-time are found to be the important parameters for the response MRR.

2. From figure 4, in case of graphite electrode material removal rate decreased with increase in gap voltage and increased with increase in peak current and pulse on time. In case of brass electrode, material removal rate increased with increase in gap voltage to a certain limit and then it decreased, material removal rate increased with increase in peak current, also material removal rate decreased with increase in pulse on time to a certain limit and then increased with increase in pulse on time.
3. From figure 5, Material removal is higher while machining with graphite tool compared with brass. Hence, it can be concluded that graphite tool is more favorable than the brass electrodes for the machining of Inconel 601 work material with an objective of having higher material removal and minimum tool wear.

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