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Modeling and Analysis of Effects of Machining Parameters on MRR in EDM Process of Copper Tungsten Metal Matrix Composite(MMC)

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Abstract: **Electro Discharge Machining (EDM) has been recognized as an efficient method of producing dies and machining of hard materials such as ceramics and high strength metal matrix composites for the modern metal industries. The large number of parameters and inherent complexity of material removal mechanism taking place in EDM make it even more difficult to select machining conditions for optimal performance. Being hard copper-tungsten MMC getting great demand from industries like aerospace, automobile and die making. In the present work, experiments were conducted using response surface methodology (RSM) with an appropriate Design of Experiments (DOE) technique to ascertain the effect of EDM process parameters on material removal rate (MRR) of Cu W MMC. The experiment plan adopts central composite design. The result of ANOVA indicates that proposed mathematical model can adequately describe performance within limit of factors being studied. Finally an attempt has been made to estimate the optimum machining condition to give best possible material removal rate within the experimental domain.**

Keyword: Electro Discharge Machining , Response Surface Methodology, DOE, ANOVA

I. INTRODUCTION

Composite materials are greatly fascinated by metal industries as they exhibit exceptional mechanical and physical properties such as high strength, high hardness, and high density at elevated temperature. Because of such extra ordinary behavior composites are finding wide range of application in the heat exchangers, die making etc. The typical processes of manufacturing composite material are compacting techniques of powder metallurgy and high temperature sintering. Producing complex shape in composite material with high dimensional accuracy is tedious work to be maintained by traditional machining technique. Electro Discharge Machining process is the best choice for machining composite like copper tungsten MMC, since there is no actual physical contact between tool and work piece during process. Drilling is considered to be a vital machining operation for composite materials to realize the structural application, miniaturized hole is necessary. Conventional drilling of similar composite is difficult for such applications where the quality hole is more crucial along with high MRR. In the present work, in all 31 numbers of experiments were conducted including confirmation test. All the experiments follow a certain sequence with all combinations of input parameters at various levels being specified. After conducting experiments the generated data is used to make mathematical model using regression analysis. The effect of process parameters on MRR is then analyzed using 3D surface plots and 2D contour plots and at the last optimum combination of process parameters is suggested which will give rise to optimum MRR. As far as EDM is concern, the major characteristics are, the process can be used to machine any material irrespective of their hardness as long as it is electrically conductive. MRR depends mainly on the thermal properties of material rather than the physical properties. The process is generally known for its accuracy to machine any integrate shape [1-3].

A. Fundamental principle of working and process parameters of EDM

In EDM, when the voltage is applied between electrode and work piece electric field set up between spark gap. As both electrode and work piece being electrically conductive possess sufficient amount of free electrons .This free electrons are plugged towards work piece because of electric field in spark gap. But in between tool and work piece dielectric fluid is present. The emitted electrons stick on dielectric molecules and ionize them. Now in spark gap there are free electrons and ions which undergo collusion due to avalanche motion between them leads to development of new state of matter called 'Plasma'. Thus plasma channel is set up between tool and work piece and the temperature goes high around 8000-12000^{o}C.Thus surface layer of work piece is rapidly melted by a spark at each charge point. In this way, small volume of work piece material is removed by mechanism of melting and vaporization because of sparking occurs. Hence it is also known as Spark Erosion Machine. Major parameters affecting the EDM process are briefly defined as follow [2]

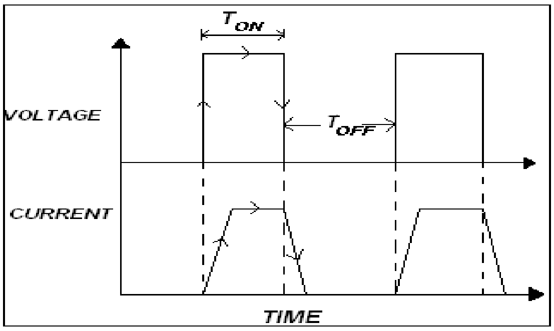

Figure: 1 Standard Wave Form of EDM

Gap voltage (Vg): It is the amount of potential difference applied in between gap of electrode and work piece, during a particular cycle for a particular period of time. Because of application of voltage electric field is generated in between tool and work piece. Once voltage is applied it remains constant for some time and then it is retracted shown by rectangular wave form in Figure1.

Discharge Current (I_P): The value of the current applied to the electrode during pulse on time. Current does not increases or lower down suddenly showing trapezoidal waveform with respect to voltage depicted in Figure1.

Pulse on time (Te): It is the time for which current is applied to the electrode during each EDM cycle. The material removal is directly proportional to the spark energy applied during pulse on time. This energy is controlled by the current and pulse on time.

Pulse off time (Toff): It is the time for which voltage is retracted during a particular cycle. Melted and solidified particles are removed from the gap during this period.

Duty Factor (U): It is a percentage of the on-time relative to the total cycle time. And generally expressed as

$$\text{Duty factor} = \frac{\text{Pulse on Time}}{\text{Pulse onTim e+Pulse off Time}} \qquad (1)$$

II. LITERATURE REVIEW

Over the years, experimentalists have tried to establish empirical models based on statistical analysis and optimization methods to rationalize the EDM process. Review presented below explores different methodologies and processes regarding enhancement of responses like material removal rate and surface roughness in EDM. Pichai Janmanee et al. [2] aimed to optimize electrical discharge machining of 90WC-10Co composite using taguchi approach to minimize micro crack density, tool wear and maximize material removal. Maximum MRR was obtained at current 75 A, Pulse off time 2 µs open circuit voltage 250 Volt. K. Ponappa et al. [3] carried out investigation of the effect of process parameters of electro discharge machining of magnesium nano alumina composites. Pulse on time, Pulse off time, voltage gap and servo speed were optimized to get better Ra and reduced taper. Ko-Ta Chiang [4] presented RSM technique of modeling of machining characteristic of Al2O3+TiC mixed Ceramic. It was concluded that MRR is greatly affected by discharge current and duty factor. S.H.Tomadi et al. [5] aimed to analyze the influence of EDM parameters on surface quality, material removal rate and electrode wear of WC-Co. Full factorial design methodology was adopted. It was found that to obtain high MRR high value of peak current and voltage should be used. Chandrasekaran et al. [6] proposed mathematical models for modeling and analysis of the effects of machining parameters on the performance characteristics in the EDM process of WC/5Ni composite which was produced through powder metallurgy route. R.A.Mahdavinejad [7] aimed to optimize electro discharge machining parameter for WC-Co work piece material and copper electrode using the neural model predictive control method. The testing results from ED machining of WC-Co confirms the capability of the system of predictive controller model based on neural network with 32.8% efficiency increasing in stock removal rate. B. Lauwers et al. [8] performed investigation of the material removal mechanisms of some commercially available electrical conductive ceramic materials through analysis of the debris and the surface/sub-surface quality. ZrO2-based, Si3N4-based and Al2O3-based ceramic materials, with additions of electrical conductive phases like TiN and TiCN were taken as workpiece materials. Debaprasanna Puhan et al. [9] represented ahybrid approach for multi response optimization of electrodischarge machining on AlSiCp MMC. S.Assarzadeh et al. [10] presented neural network based modeling for prediction and optimal selection of process parameter in die sinking EDM with flat electrode. 3-6-4-2 Size back propagation neural network was developed to establish the process model. Ozlem Salman et al. [11] demonstrated evolutionary programming method for modeling electro discharge machining parameters for roughness. Murli M. Sundaram et al. [12] experimentally studied the performance of copper-graphite as tool material in micromachining by micro electro discharge machining. N.Y. Tantra et al. [13] evaluated theoretical equations to predict wear in electro discharge machining. S.S. Baraskar et al. [14] performed mathematical modeling of electro discharge machining process using response surface methodology. MRShabgard [15] carried out mathematical modeling of machining parameters in electro discharge machining process of FW4 welded steel. Harshit Dave et al. [16] carried out investigations on prediction of MRR and ANN programming methodology.

The literature above reveals that the lots of efforts were taken in order to rationalize the EDM process. However a little work has been reported on the modeling and analysis of effects of machining parameters on the performance characteristic in EDM process of copper tungsten metal matrix composite. In the present work Response surface methodology (RSM) with an appropriate design of experiments (DOE) is used to investigate the relationship and parametric interactions between four input variables namely current, voltage, and pulse on time and duty factor on material removal rate of Cu-W(30-70) % metal matrix composite material. The Material is so chosen because of considering its applications in industrial areas such as die making, aerospace, automobile where high degree of accuracy is required along with high MRR.

III. EXPERIMENTAL PROCEDURE

A. Work piece Material

For experimental purpose Cu-W (30-70) % metal matrix composite material was selected. Cu-W MMC have good heat résistance, ablation resistance and thermal resistance properties and finds wide range of applications such as aerospace engine nozzle, chip carrier heat sink etc. which have integrated shapes. Cu-W MMC has hardness 90B, density14.18g/cm^3, Thermal conductivity 2.01 W/cm °C and melting point of 3140^{0}C. Figure 2 reveals the micro structure of copper tungsten metal matrix composite in which copper particles are dispersed randomly in the matrix of tungsten.

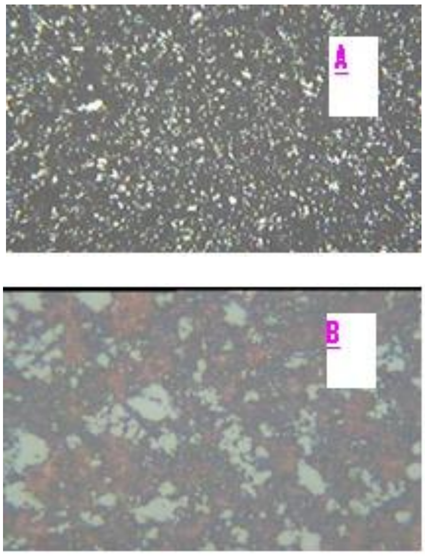

Figure 2 Microstructure of Cu-W MMC (A) 100X (B) 1000X

For experimentation purpose 30 numbers of holes are drilled of diameter 7.5 mm over two square plates of size (55x 55x 5) mm.

B. Electrode Material

With the advancement in EDM, copper becomes the metallic electrode material of preference. Again due to its tool making culture that is averse to the 'untidiness' of working with graphite, copper is generally preferred as electrode of choice. For experimentation purpose copper Electrodes of diameter 7.5 mm as shown in Figure3 were employed. Separate electrode was used for experimentation to retain accuracy of the process.

Figure 3 Machined Work piece and Copper Electrodes

C. Machine Tool and Dielectric medium

All the experiments were performed on die sinking 'ZNC-ELETRONICA EDM MACHINE' of 'S-ZNC SERIES' having definable erosion axis. For experimentation purpose "RUST LICK-30" oil having dielectric strength 45KV was used as a dielectric medium at a flushing pressure of 0.25Kg/CM^2. Dielectric fluid should possess two conflicting properties that, it is the spark conductor that must ionize under the applied voltage at the same time it should not get break down in spark gap. It should act as a flushing medium that carries away the melted material.

Figure 4 ZNC-ELECTRONICA EDM Machine

A jet flushing system along with quill of EDM machine is shown in Figure 4. Jet flushing was adopted to assure adequate flushing of the debris from spark gap.

D. Machining performance evaluation

Material removal rate is expressed as the ratio of the difference of weight of the work-piece before and after machining to the machining time and density of the material. Material removal rate is regarded as 'larger-the-better' characteristic and evaluated as [5, 7]

$$\text{MRR}=\frac{1000\times\text{Initial Wt.}-\text{Final Wt.}}{\text{Density }(\rho)\times\text{machining time }(t)}\quad(\text{mm}^3/\text{min})\qquad(2)$$

Where, t= Machining time (min)
Initial Wt = Weight of work piece before machining (g)
Final Wt = Weight of work-piece after machining (g)
ρ=Density of Cu-W composite=14.18g/cm^3

IV. RESPONSE SURFACE MODELING

Response surface methodology is a collection of mathematical and statistical technique that is useful for modeling and analysis of problems in which a response of interest is influence by several variables and the objective is to optimize the response in the RSM, The process yield is a function of the levels as

$$Y= f(x_1, x_2) + e$$

Where e represents the noise observed in the response Y. If we denote the expected response by E(y) = f(x$_1$, x$_2$) = h, then the surface represented by h = f(x$_1$, x$_2$) is called the response surface. The quantitative form of relationship between the desired response and independent input variables can be represented as follow

$$Y = f\ (\mathrm{Vg, Ip, Te, U})$$

Where Y is the desired response and f is the response function. In the procedure of analysis, the approximation of y is proposed using quadratic model. The quadratic model is exactly suitable for studying carefully the interactive effects of combinative factors on the performance evaluations. The quadratic model of y is given as

$$Y = a0 + \sum_{i=1}^{4} aixi + \sum_{i=1}^{4} aiixi2 \sum_{i<1}^{4} aijxixj \qquad (3)$$

Where a_0 is constant, $a_{1,}$ a_{ii} and a_{ij} represents the coefficient of linear, quadratic and cross products terms respectively. x_i reveals the coded variables corresponding to the studied machining parameters. The quadratic model works quit well over the entire factor space and the regression coefficients are computed according to least square fit. Using the quadratic model of f in these study not only aims to investigate the response over the entire factor space but also aims to locate the regions of the desired target where the response approaches its optimum or near optimize value. Using response surface methodology with an appropriate experimental design (DOE) is an appropriate method of finding responses. In RSM, experiments are conducted which follow a certain sequence with all combinations of input parameters at various levels. Some of the experiments are repeated during process in order to enhance the accuracy of process [2, 14].

V. DESIGN OF EXPERIMENTS

In the present investigation, experiments were performed on the basis of the Design of Experiments (DOE) technique. Central composite rotatable design (CCD) was employed for experimentation in order to improve reliability of result and to reduce the size of experimentation without loss of accuracy. The design chosen was a factorial design 2^4 with 16 cube point,4 center point in cube,8 axial point and 2 centre point in axial. The process parameter selected for the experimentation were current, voltage, pulse on time, and duty factor, and MRR as proposed response. The levels for the each variable were chosen as -2,-1, 0, +1, and +2 to have rotatable design. The coded value for intermediate value of the variable can be calculated as

$$\mathrm{Xi}=2\times \left[\frac{2X-(Xmax+Xmin)}{(Xmax-Xmin)}\right] \qquad (4)$$

Where Xi, is the required value of variable X, X any value of the variable from Xmin to Xmax, Xmin is the lower limit of the variable and Xmax upper limit of the variable. For the four variable chosen the Central Composite design required 30 experiments to perform. The experiments were carried out according to the run order provided in the experiment design matrix given in table. Also all the results obtained are systematically summarized .At the end of each run, setting for all four parameters were changed and reset for the next run. This was essential to introduce variability in the experimental settings. Table I represents the parametric variation chart containing process parameters along with their various levels used in experimentation.

TABLE I Parametric Variation Chart

Parameters	Levels				
	-2	-1	0	+1	+2
Current (I_P)	34	38	42	46	50
Voltage (V_g)	80	90	100	110	120
Pulse on time (T_e)	500	750	1000	1250	1500
Duty Factor (U)	2	4	6	8	10

VI. RESULTS AND DISCUSSION

As mentioned earlier 30 experiments were conducted and value of MRR along with the design matrix is listed in Table V. The obtained results are then used to generate mathematical model using regressing analysis. The generated regression equation is

MRR= -2.40 +0.082 Current +0.0033 Voltage +

0.00098 Pulse on Time+0.0260 Duty Factor (5)

TABLE II Pre- ANOVA Model Summary Statics of MRR

Predictor	Coef	SE Coef	T	P
Constant	-2.4022	0.2468	-9.73	0.000*
Current	0.081979	0.004016	20.41	0.000*
Voltage	0.003375	0.001606	2.10	0.046*
Ton Time	0.00098167	0.00006426	15.28	0.000*
Duty Factor	0.026042	0.008032	3.24	0.003*
*Denotes Significant Terms				

S=0.0787 R-Sq = 96.4% R-Sq (adj) = 95.8% R-Sq (pred) = 94.34%

The ANOVA and Fisher’s statistical test (F-test) were performed to check the adequacy of the model as well as the significance of the individual parameters Table II shows the pre ANOVA model summary statics of MRR. In the table IV variance analysis results of the proposed model of MRR is presented. The ANOVA table includes sum of squares (SS), Degree of freedom (DF), Mean Square (MS), F-value and P-value The MS was obtained by dividing the SS of each of the sources of variation by the respective DF. The ‘P’ value is the smallest level of significance at which the data is significant. F value is the ratio of MS of the model term to the MS of residual.

The values of ‘P’ for the terms of model are less than 0.05 (i.e. α=0.05, or 95% confidence) indicates that the obtained model is considered to be statically significant. It is noted that MS of the model 1.0297 is many times larger than MS of the residual (0.0062) thus the computed F-value of the model (F=1.0297 /0.0062) of 166.24 implies that the model is significant. The other important coefficient is R^2 called as determination coefficient and is explained as the ratio of variability explained by the model to the total variability in the actual data and is used as a measure of degree of fit. Table II shows the "R-Squared (Adjust R^2)" and "predicted R-Squared (Pred. R^2)" statics. As R^2 approaches unity better the fit of experimental data and there exists less difference between the predicted and actual value of R^2.For the model value of R^2 is 0.964 implies that the model explains variations in the MRR to the extent of 96.4% in the given experiment and thus the model is adequate to represent the process.

TABLEIII ANOVA Model Summary Statics of MRR

Source	DF	SS	MS	F	P
Regression	4	4.118	1.0297	166.24	0.000*
Residual Error	25	0.1548	0.0062		
Total	29	4.2735			
*Denotes Significant Term					

TABLE IV Design Layout and Experimental Results

Run order	Actual Factors				MRR (mm^3/ min)
	Current (I_P)	Voltage (V_g)	Ton (T_e)	Duty Factor (U)	
1	42	100	500	6	2.00
2	42	100	1000	6	2.51
3	42	100	1000	6	2.53
4	42	100	1000	2	2.41
5	42	100	1500	6	2.95
6	34	100	1000	6	1.81
7	42	120	1000	6	2.56
8	42	100	1000	10	2.55
9	42	80	1000	6	2.45
10	50	100	1000	6	3.23
11	46	90	750	4	2.59
12	42	100	1000	6	2.52
13	46	110	1250	8	3.13
14	46	110	750	8	2.68
15	42	100	1000	6	2.53
16	46	90	1250	4	3.00
17	38	90	750	8	1.97
18	42	100	1000	6	2.51
19	38	90	750	4	1.88
20	38	90	1250	4	2.33
21	46	90	750	8	2.63
22	46	90	1250	8	3.10
23	38	110	750	8	1.92
24	46	110	1250	4	3.00
25	46	110	750	4	2.59
26	38	110	1250	4	2.38
27	38	110	750	4	1.95
28	42	100	1000	6	2.52
29	38	90	1250	8	2.41
30	38	110	1250	8	2.85

'Predicted R^2' of 94.34% is in reasonable agreement with the 'Adjusted R^2' of 95.8% because the difference between adjusted and predicated R^2 is needed to be within 0.2 as recommended for the model to be adequate. The value of 'Pred.R^2' of 0.9434 indicates the prediction capability of regression model. It means that the model explain about 94.34% of the variability in predicting new observations as companied to 96.4% of the variability in the original data explained by the least square fit. Lower 'S' (Standard error of regression) value implies better prediction of response by the equation. 'S' value of model is 0.0787 suggests that the model is significant. Thus the overall prediction capability of the model based on these criteria seems very satisfactory. Further the difference between experimental and predicted values of MRR is illustrated in Figure 5. The results of comparison show that the value of MRR is close to those readings recorded experimentally with a 95% confidence level [14].

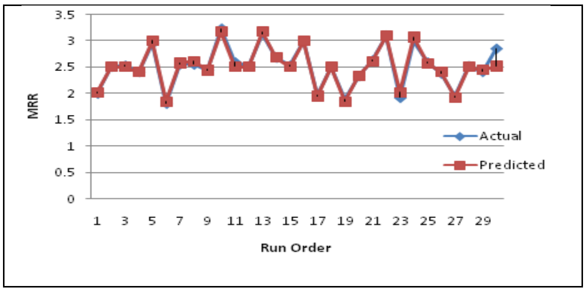

Figure 5 Comparison of Calculated and Predicted Value for MRR

A. Average Prediction error evaluation

Prediction error has been defined as follows [14]

$$\text{P.E. } (\%) = \frac{\text{Predicted value-Experimental value}}{\text{Predicted value}} \times 100 \qquad (6)$$

The predicted values and the calculated values are compared and error and percentage error was evaluated as above. An average prediction error of regression analysis validation is found to be 1.55% which reflects the soundness of model.

VI. ANALYSIS OF MRR

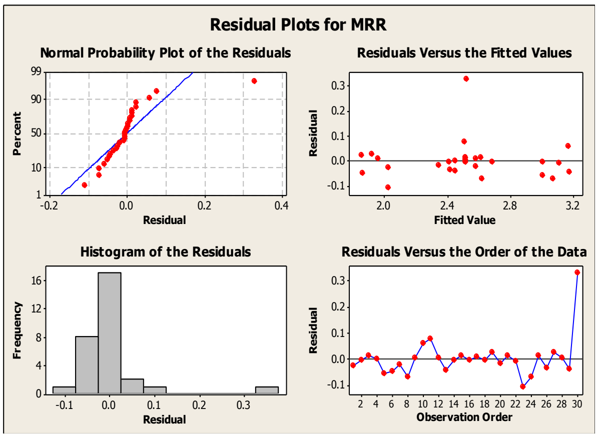

Figure 6 Residual Plots for MRR

Figure6 shows the residual plots for MRR obtained through MINITAB14 SOFTWARE [17]. Normal probability plot of residuals reveals that residuals fall on a straight line implies that the errors are normally distributed. Residuals versus the fitted values graph shows that residuals appear to be randomly scattered about zero, reveals that the constant variation is observed between residuals and fitted values. Residuals versus order plot graph shows that residuals are fluctuating in random pattern around the centre line implies no evidence exists expressing the error term are correlated with one another. Histogram proves that data are not skewed.

Figure7 depicts the effect of discharge of current and pulse on time on the value of MRR under the duty factor of 6 and discharge voltage of 100 V. The MRR is shown to continuously increase with an increase of discharge current. With increase in spark energy which is directly proportional to current more and bigger crater are observed on the machined surface, resulting in high stock of material removal. Same trend is observed for pulse on time i.e. value of MRR is shown to increase with an increase of pulse on time, up to 1000µs, and then decrease with a further increase in the pulse on time. This event has been attributes to the increase of input energy in the high plus on time, which results in more chopping on the gap between the work piece and the electrode, and hence it creates a short circuit and decreases the efficiency of electrical spark-erosion. Optimum value of MRR is around 2.50 mm^3/min is observed near to 42A discharge current and around 1000µs pulse on time. Also from the contour plot presented in Figure 8 MRR shows continuous raise with increase in current it is because of increase in current value leads to increase in spark energy across electrode gap. Also with increase in pulse on time MRR increases due to rapid melting and vaporization and tends to decrease with further increase in pulse on time.

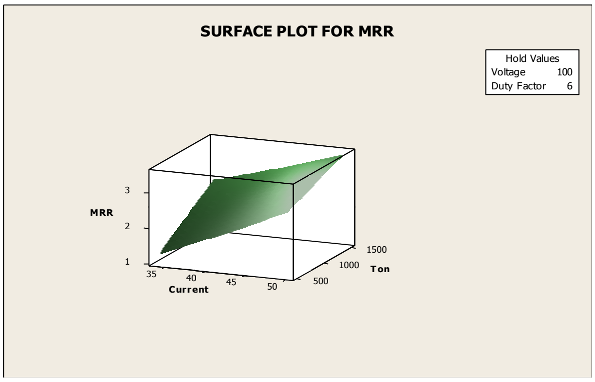

Figure 7 Effect of Current and Pulse on time on MRR

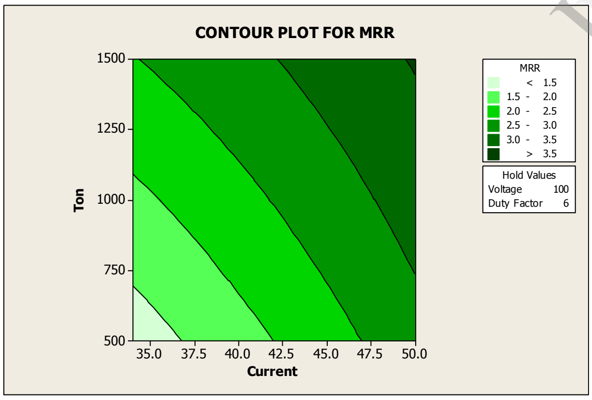

Figure 8 Effect of Pulse on time and Current on MRR

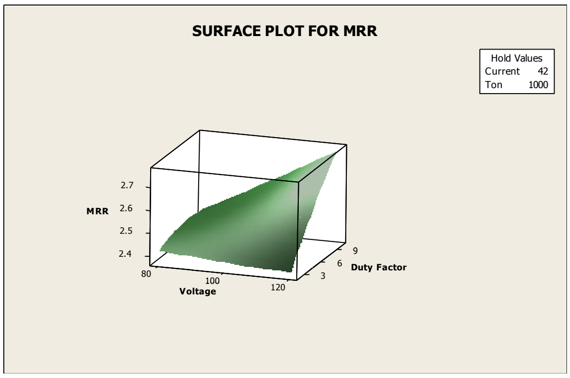

Figure 9 Effect of Voltage and Duty factor on MRR

Figure 9 reveals the effect of duty factor and open discharge voltage on the value of MRR under the discharge current of 42A and pulse on time of 1000 µs. In general, both the duty factor and the open discharge voltage determine the status of input energy in the EDM process. From above surface plot it can be seen that that an increase in both duty factor and the voltage leads to an increase of MRR. Increase of voltage means that the electric field becomes stronger and the spark discharge occurs more easily under the same gap. The increase of the duty factor means applying the spark discharging time for a long time and this will cause an increase in the discharge times and machining efficiency, and subsequently an increase in the amount melted material removal. More surface area is concentrated around voltage of 100V and duty factor 6 implies optimum MRR.

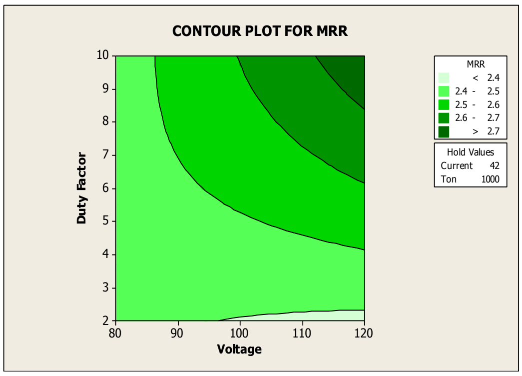

Figure 10 Contour Plot of MRR

Figure 10 depicts the contour plot for MRR under the variation of voltage and duty factor .By observing contour line and contour area it is clear that optimum value of MRR around 2.50mm^3/min is observed for the voltage 100V and duty factor 6.Also from contour plot values of voltage and duty factor can be estimate for a particular value of MRR.

A .Confirmation Experiment

TABLE V Result of the Confirmation Experiment

Experiment	Actual Factors				MRR (mm^3 /min)
	Current	Voltage	Ton	Duty Factor	
Actual	42	100	1000	6	2.53
Predicted	42	100	1000	6	2.52

TABLE V reveals the result of confirmation experiment conducted for optimum parameters setting and the difference of 0.39% between actual and predicted response is evaluated.

VIII. CONCLUSIONS

In this investigation, mathematical model of MRR was evaluated to correlate dominant machining parameters including the discharge current, voltage, and pulse on time and duty factor to maximize MRR. The influence of machining parameters on the performance characteristics in the EDM process of Cu-W MMC were based on the developed mathematical model to yield the following conclusions

1) The results of ANOVA and residual plots represent that the mathematical model of the value of MRR is fairly fitted with the experimental values with a 95% confidence interval.

2) Experimental values of MRR can satisfactorily be predicted from experimental diagrams of response surface and contour graph. Also an average prediction error of regression analysis validation is found to be 1.55% indicates that the obtained model is considered to be statically significant. Also confirmation test reveals that the negligible difference is present between actual and predicted value of MRR.

3) The two main significant factors affecting the value of the MRR are the discharge current and pulse on time, whereas voltage has least statistical significance on values of MRR.

4) The value of MRR steadily increases with increase in values of current and pulse on time. In case of voltage and duty factor, value of MRR first increases and then starts decreasing with further increase in values of voltage and duty factor.

5) The optimum value of MRR 2.53 mm^3/min is observed at discharge current of 42A, voltage 100V, and pulse on time 1000 µs and at duty factor of 6 within experimental domain.

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