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MODELING OF WEDM PARAMETERS WHILE MACHINING MG-SIC METAL MATRIX COMPOSITE

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ABSTRACT

In this paper an attempt has been made to study the effects of the process parameters of wire cut electrical discharge machining (WEDM) on Magnesium-Silicon Carbide MMC with 5% SiC in particulate form. For the analysis, six factors, namely pulse on time, pulse off time, spark gap voltage, peak current, dielectric flushing pressure and servo feed have been taken and a Taguchi L16 orthogonal array for two levels was used. Response surface methodology was also used to develop second-order models for material removal rate (MRR) and surface roughness (SR). From the analysis of variances, it has been observed that pulse on time and pulse off time were the most significant parameters among all those observed in predicting the MRR and SR, respectively.

Keywords: ANOVA; Mg-SiC; MMC; MMR; WEDM

1. INTRODUCTION

A desire and thirst for gaining a better understanding of the universe in the 1960's led to an era of space-age exploration and development of modern technologies. Conventional metals were unable to meet the requirements of extreme properties that were required in those kinds of harsh operating conditions. High-speed automobiles and developments in the aerospace field created such extreme temperature and pressure conditions inside an engine cylinder that there was an urgent need to replace conventional metals. The extreme operating conditions of such hostile environment raised the demand for new age, exotic composite materials. Among those exotice new materials are Material Matrix Composites (MMCs), which are obtained by reinforcing a metal or alloy with a high strength ceramic materials, such as silicon carbide, aluminum oxide, etc. Recently, magnesium alloys have found increased applications in automobile and aerospace industries because of their lightweight properties. The density of magnesium is approximately two-thirds of aluminum and one-fifth of that of steel (Saurav & Mahapatra, 2010). Due to this low density, the specific strength of magnesium is very high, when compared to other metals. However, the use of magnesium is limited to only low temperatures. For use at elevated temperatures, magnesium alloys are not suitable. The need for exotic advanced materials to be able to sustain high temperatures along with lightweight properties led to extensive R&D of magnesium matrix composites. One of the advantages of MMCs is that the constituent selection is flexible and so the properties of the materials can be customized. The main disadvantage is the relatively high cost of fabrication, due to which a cost-effective manufacturing process must be adopted so as to reduce material loss and also to produce intricate shapes and profiles.

One such machining process is the wire cut electrical discharge machining (WEDM) process.

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WEDM in recent years emerged to be the most widely-used machining process with its outstanding ability to cut intricate shapes and designs without taking into account the hardness and other mechanical properties of the material (Ho et al., 2004). The principle of WEDM is illustrated in Figure 1. The mechanism of WEDM is similar to that of conventional EDM where the material is removed by erosion, due to the spark generated. However, in the case of WEDM, a reel of wire is continuously fed into the process. As the wire moves through the work piece for cutting the desired shape, the wire is fed from a supply reel to a take-up reel and a fresh wire of constant diameter is passed through the material every time so as to maintain a constant cut width throughout. One big disadvantage of WEDM is its very low material removal rate which is challenging its viability as a prominent technique to machine exotic advanced materials. Due to this situation, several types of research have been carried out to understand the effects of process parameters on the response characteristics like those of material removal rate (MRR) and surface roughness (SR) and optimize these characteristics to obtain the best performance rates, especially for MMCs. It has been found out that of the researches carried out in the field of machining MMC with EDM and WEDM, 71% of the studies are conducted on WEDM and 21% of these are in EDM (Kumar et al., 2012). Furthermore, of the studies conducted in WEDM, 22% are on optimizing the process parameters and 45% are on monitoring and controlling those process parameters (Ho et al., 2004). However, the studies, while machining magnesium MMCs for machining optimization of WEDM process parameters, have been very few. Kumar et al. (2014) investigated the relationship of the process parameters in WEDM of Mg-SiC 10% and 20% using molybdenum wire as the electrode. The response characteristics selected were MRR and SR. An L9 Taguchi orthogonal design was selected. An optimal set of process parameters were found for both MRR and SR, using signal-to-noise (S/N) ratio analysis. Furthermore, the grey relational analysis was also performed for multi-objective optimization and an optimal parameter set was revealed. Sharma et al. (2013) developed a second order model using response surface methodology (RSM) to establish the relationship between WEDM parameters, such as pulse on time, pulse off time, spark gap voltage, peak current and wire tension with MRR and SR. Shandilya et al. (2012) performed the WEDM of SiC/6061 Al MMC having 10% of SiC particles using brass wire as an electrode. Kerf width was selected as the response characteristic. A total of 29 experiments were conducted using Box Behnken Design (BBD) for four parameters and a second-order model was developed for the kerf width using RSM. The effects of the process parameters on kerf width were studied and also the surface integrity of the machine surface was examined.

Subrahmanyam and Sarcar (2013) used the Grey-Taguchi method for the multi-objective optimization of WEDM parameters while machining hot die steel H13. MRR and SR were selected as the responses. An optimal set of parameters was revealed. Analysis of variance for the overall grey relation grade was done and the significance of the process parameters was found out. Furthemore, mathematical models were also developed for the responses. Satishkumar et al. (2011) investigated the effects of process parameters of WEDM on unreinforced Al6063 and also Al6063 reinforced with SiC 5%, 10%, 15% with a brass wire as an electrode. An L9 Taguchi orthogonal array was used and responses that were selected are MRR and SR. Linear models were developed using regressions for MRR and SR at each percentage variation of SiC. Analysis of variance was performed to study the significance of each parameter on the output responses. Puri and Bhattacharyya (2004) studied the effects of process parameters on white layer depth occurring while machining with WEDM. A rotatable Central Composite Design (CCD) was used and response surface methodology was applied to develop the mathematical models. Analysis of variance was performed to find the parametric influences of white layer depth.

In WEDM, the most significant response characteristics are the material removal rate (MRR) and surface roughness (Ra). MRR stands out to be an index for productivity and surface roughness for quality. The desired requirement is that MRR should be high and Ra should be low. However, both the response characteristics are conflicting in nature and therefore an efficient method is needed to be adopted so as to optimize the process parameters to achieve the optimum machining performance. In this paper, an attempt is made to study the effects of each parameter of WEDM on MRR and SR using the Taguchi Grey Relational Analysis and to find out an optimal parameter setting. Furthermore, three of the most significant parameters will be subsequently selected from the preliminary analysis and further experiments will be conducted to develop second order models using response surface methodology.

2. EXPERIMENTAL SET-UP

The principle of WEDM is illustrated in Figure 1. Figure 1 shows a schematic arrangement of WEDM process and surface roughness measurement of Mg-SiC.

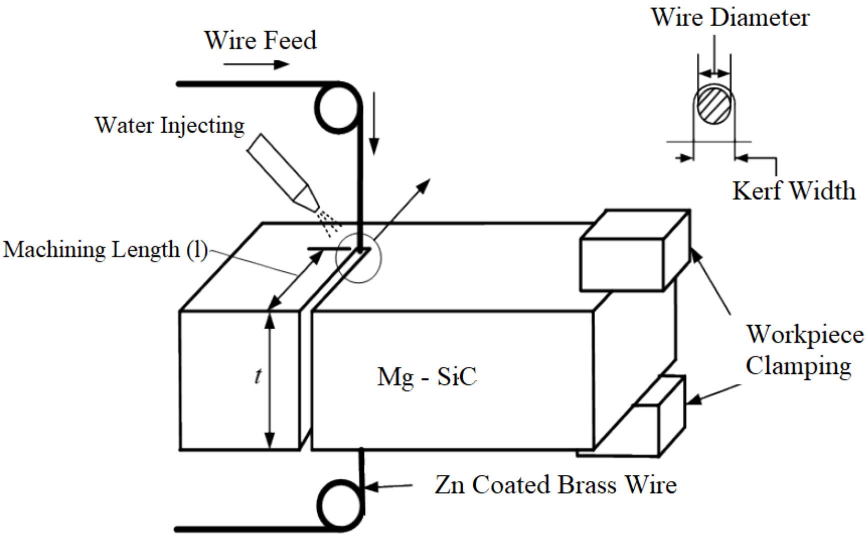


Figure 1 Schematic diagram of WEDM process

2.1. Material and Tool Selection

The experiment was performed in a CNC wire EDM, shown in Figure 2, using Mg-SiC (5%) as work piece material and zinc coated brass wire of 0.25 mm diameter as an electrode. The work piece material used for machining is shown in Figure 3. The dielectric fluid was de-ionized water. The MRR is expressed as the ratio of the difference in weights of the material before and after machining in relation to the machining time. The surface roughness was measured using a portable surface roughness tester. The values for surface roughness were taken at three locations for a particular machined surface after every experiment and their mean value was also taken.

2.2. Design of Experiment

During the WEDM machining experiment, a few parameters were kept constant to analyse the performance characteristics in more detail (Saurav & Mahapatra, 2010). Table 1 gives the list of the constant parameters along with their values.

Figure 2 CNC wire cut electrical discharge machining

Figure 3 Work piece material Mg-SiC (5%)

Table 1 Parameters held constant during the experiments

Parameters	**Values**
Work piece material	Mg-SiC (5%)
Electrode material	Zinc coated brass (0.25 mm diameter)
Wire feed rate	4 m/min
Wire tension	500 g
Cutting speed	50 m/min

In the present work, three of the most significant parameters while machining Mg-SiC in wire EDM are pulse on time (T_{ON}), pulse off time (T_{OFF}) and gap voltage (SGV), which were selected as input parameters having three levels as given in Table 2.

Table 2 Process parameters and their levels

Process Parameters	Units	Level 1	Level 2	Level 3
Pulse on time (T_{ON})	μs	110	113	116
Pulse off Time (T_{OFF})	μs	57	60	63
Gap Voltage (SGV)	V	15	20	25

A Box Behnken Design (BBD) of the experiment having 15 datasets from RSM was employed. The BBD experimental design matrix and responses are given in Table 3.

Table 3 Experimental results for BBD with three parameters and three levels

Experiment No.	T_{ON} (μs)	T_{OFF} (μs)	SGV (V)	MRR (mg/min)	SR (μs)
1	110	63	20	21.627	2.692
2	110	60	15	30.345	3.177
3	116	57	20	37.770	4.433
4	113	63	15	39.231	3.249
5	110	60	25	29.707	3.127
6	110	57	20	31.832	4.372
7	113	60	20	54.615	3.772
8	113	60	20	53.265	3.603
9	116	60	15	29.943	3.335
10	116	60	25	36.071	3.216
11	113	60	20	51.915	3.430
12	116	63	20	40.260	3.689
13	113	57	15	35.615	3.859
14	113	63	25	32.054	3.093
15	113	57	25	53.906	3.995

3. RESPONSE SURFACE METHODOLOGY

Taguchi Grey relational analysis is inefficient in studying the effects due to the higher order polynomials. To understand the effects in the responses due to a curvature, higher order models need to be developed. Response surface methodology (RSM) is a collection of mathematical and statistical techniques that are used for modeling and optimizing the process parameters of complex physical processes and their relationship to the output responses of the process (Myers et al., 2009). With the help of RSM, a second-order model can be developed and the quadratic and interaction effects of the process parameters can be studied. The output response can be modeled according to the second order model as shown in Equation 1 below:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j} \beta_{ij} x_i x_j + \varepsilon \tag{1}$$

Where y is the output response, x_i, x_j, x_k are the input process parameters, β_0, β_i, β_{ii}, β_{ij} are the regression coefficients and ε is the random error.

3.1. Mathematical Modeling

Table 4 shows the analysis of variance for the second order model obtained for MRR and SR. The P-values associated with the models are well below 0.05 and thus the model is statistically significant. Furthermore, the table also shows the values of R^2 and R^2 adjusted. The value of R^2 describes the amount of variation in the responses that is explained by the model. It is the ratio of the variability explained by the model to the total variability in the data (Raghuraman et al., 2013). The higher the value of R^2, the fitter the model is. However, the inclusion of insignificant parameters may artificially increase the value of R^2. To solve this problem, a term called R^2 adjusted is introduced which takes into account the addition of predictors in the model. Unlike the R^2 adjusted, R^2 may get smaller when insignificant parameters are added to the model. A smaller difference in R^2 and R^2 adjusted indicates a fitter model with significant parameters.

Table 4 Analysis of variance for models of MRR and SR

Responses	R^2	Adj R^2	P-value
MRR	95.69%	87.93%	0.006
SR	92.60%	79.28%	0.023

The R^2 and R^2 adjusted for both the models of *MRR* and *SR* are high and also the differences between R^2 and adjusted R^2 are sufficiently smaller. This establishes that both the models of *MRR* and *SR* are adequate. To understand the significance of each process parameters on the individual responses, the analysis of variance for the parameters for both the models was performed and is illustrated in Table 5. It also depicts the coefficients associated with each variable.

Table 5 Analysis of variance and coefficients of process parameters for *MRR* and *SR*

Parameters	Model for MRR						Model for SR					
	Coeff.	Seq SS	Adj SS	Adj MS	F	P	Coeff.	Seq SS	Adj SS	Adj MS	F	P
T_{ON}	342.9	116.53	644.98	644.98	49.83	0.001	0.280	0.21	0.000	0.0004	0.01	0.929
T_{OFF}	45.6	84.18	23.64	23.63	1.83	0.235	-6.539	1.94	0.485	0.4587	9.82	0.026
SGV	24.7	34.46	32.24	32.25	2.49	0.175	0.926	0.00	0.045	0.0454	0.92	0.382
T_{ON}^2	-1.6	691.10	780.48	329.12	60.29	0.001	-0.008	0.70	0.018	0.0182	0.37	0.571
T_{OFF}^2	-0.7	104.31	126.53	780.47	9.77	0.026	0.029	0.02	0.259	0.2594	5.24	0.071
SGV^2	-0.3	191.92	191.92	126.52	14.83	0.012	-0.013	0.31	0.373	0.3727	7.53	0.041
$T_{ON}\times T_{OFF}$	0.4	40.29	40.29	191.92	3.11	0.138	0.026	0.37	0.219	0.2190	4.43	0.089
$T_{ON}\times SGV$	0.1	11.44	11.44	40.29	0.88	0.390	-0.001	0.24	0.001	0.0012	0.02	0.883
$T_{OFF}\times SGV$	-0.4	162.15	162.15	11.45	12.53	0.017	-0.005	0.22	0.021	0.0213	0.43	0.541

The analysis of variance for the variance showed that pulse on time was the most significant parameter among all the others. Furthermore, the quadratic effects were more significant than the linear effects. The quadratic effects of pulse on time, pulse off time and gap voltage were found out to be statistically more significant. Also, the interaction effect between pulse off time and gap voltage was found out to be statistically significant.

Furthermore, pulse off time was found out to be statistically significant. The quadratic effect of gap voltage was also significant in predicting the *SR*. The interactions between the parameters did not have as much statistical significance on the model for *SR*.

The mathematical models associated with *MRR* and *SR*, have been developed by multiple regression analysis and are illustrated by Equations 2 and 3, respectively. All the regression and graphical analysis of the data obtained were performed using ‘MINITAB 16’ software.

$$\begin{aligned} MRR = -20981.9 + 342.9\,TON + 45.6\,TOFF + 24.7\,SGV - 1.6\,TON^2 \\ - 0.7\,TOFF^2 - 0.3\,SGV^2 + 0.4\,TON \times TOFF + 0.1\,TON \times SGV \\ - 0.4\,TOFF \\ \times SGV \end{aligned} \tag{2}$$

$$\begin{aligned} SR = {} & 176.556 + 0.280\ TON - 6.539\ TOFF + 0.926\ SGV - 0.008\ TON^2 \\ & + 0.029\ TOFF^2 - 0.013\ SGV^2 + 0.026\ TON \times TOFF - 0.001\ TON \\ & \times SGV - 0.005\ TOFF \times SGV \end{aligned} \tag{3}$$

The normal probability plots of the residual for *MRR* and *SR* are shown in Figure 4 and Figure 5 respectively. The plots show the performance of the model. If the points are not in the straight line, then the model is found to be not as effective and errors are distributed unevenly, which is not what is required for a good model. In the present work, all the points are in straight line pattern, which shows no sign of violating a perfect model. This shows that the present RSM model can be used for further investigation.

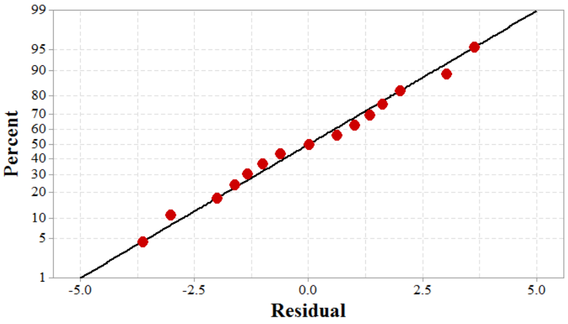


Figure 4 Normal probability of the residuals for *MRR*

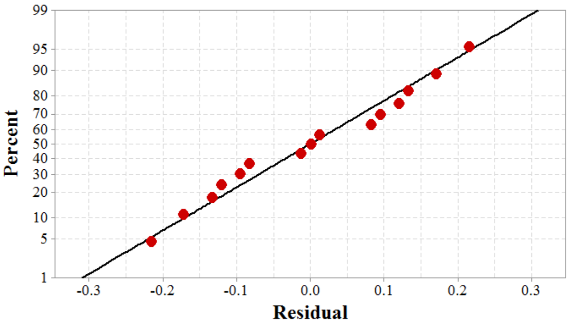
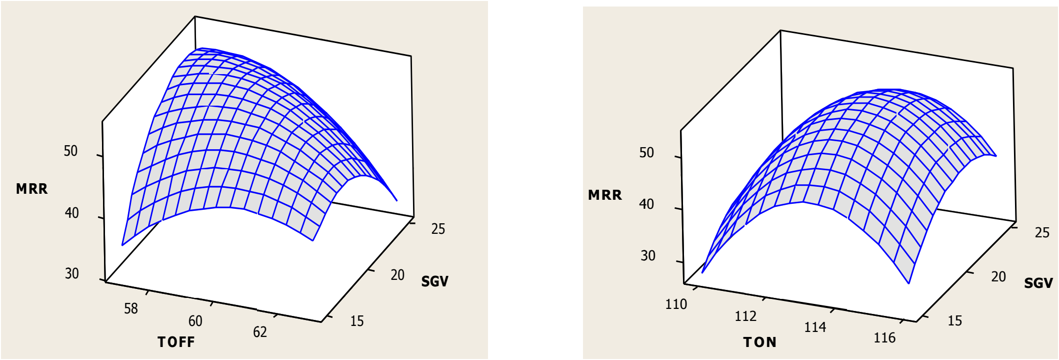


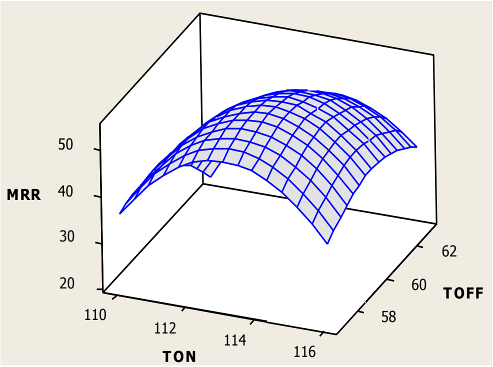
Figure 5 Normal probability of the residuals for *SR*

3.2. Effects of Process Parameters on Responses

The effects of process parameters on the responses can be better understood from the surface plots of the parameters against the responses. Figure 6 and Figure 7 show the surface plots for all the parameters against *MRR* and *SR*.



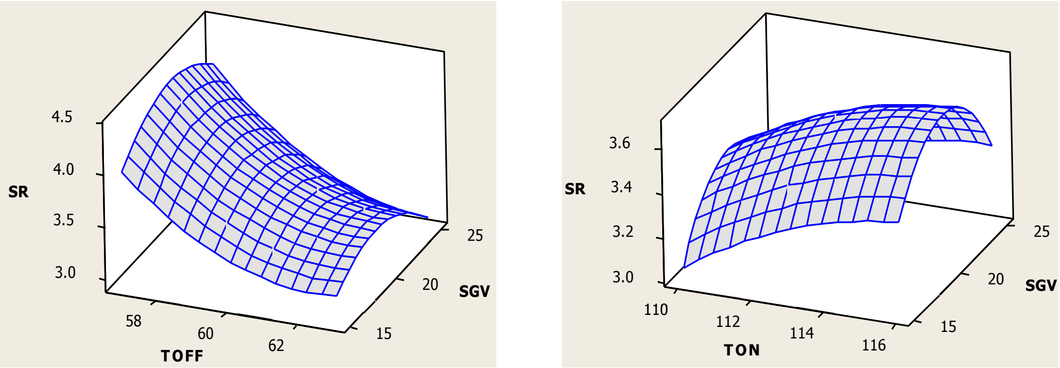
(a) Variation of T_{OFF} with *MRR* and *SGV* (b) Variation of *SGV* with *MRR* and T_{ON}



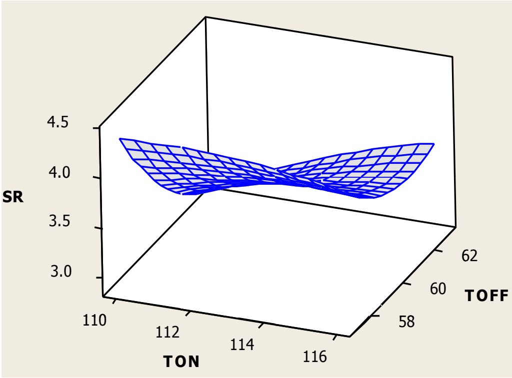
(c) Variation of T_{OFF} with *MRR* and T_{ON}

Figure 6 Interaction effects of process parameters on *MRR*

Figure 6a shows that to achieve a better *MRR*, pulse off time should be kept low along with a medium value of gap voltage. Figure 6b shows that the zone of high *MRR* is where the T_{OFF} and *SGV* both are kept at higher values. It also shows the fact that with a gradual increase in T_{ON}, *MRR* even decreases. Furthermore, Figure 6c reveals that zones of high *MRR* are somewhere around the centre of the plot when both T_{ON} and T_{OFF} are set to a medium value.



(a) Variation of *SGV* with *SR* and T_{OFF} (b) Variation of *SGV* with *SR* and T_{ON}



(c) Variation of T_{OFF} with *SR* and T_{ON}

Figure 7 Interaction effects of process parameters on *SR*

From Figure 7a it is clear that to achieve a minimum *SR*, pulse off time must be kept higher. Similarly, minimum *SR* zones in Figure 7b are when pulse on and gap voltage are set to low values. Again from Figure 7c, it is seen that surface roughness dips to the lowest values when pulse on time is decreased and pulse off time is increased.

4. CONCLUSION

In this study, an experimental investigation on wire cut electrical discharge machining (WEDM) was performed using magnesium-silicon carbide (5%) MMC as the work piece material and zinc-coated brass wire of 0.25 mm diameter was used as the electrode. The experiments were designed using a Box Benhken RSM Design. The following conclusions were made during the course of the work: (1) Mathematical models for both *MRR* and *SR* were developed and the models were found to be quite adequate; (2) The analysis of variance for the process parameters showed that pulse on time was the most significant parameter among all of the parameters in predicting the *MRR*. Furthermore, the quadratic effects were more significant than the linear effects. The quadratic effects of pulse on time, pulse off time and gap voltage were found out to be statistically more significant. Also, the interaction effect between pulse off time and gap voltage was found out to be statistically significant; (3) For *SR*, pulse off time was found out to be statistically significant. The quadratic effect of gap voltage was found to have a significant effect on *SR*.

5. ACKNOWLEDGEMENT

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