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# MULTI-RESPONSE OPTIMIZATION OF SPARK GAP AND MATERIAL REMOVAL RATE FOR THE MACHINING OF AL/ZRO2 PARTICULATE REINFORCED MMC DURING WIRE-EDM

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**ABSTRACT**

This paper presents an experimental investigation of the material removal rate and spark gap and the effect of wire EDM process parameters during machining of newly developed Al/ZrO2(p) metal matrix composite (MMC) material. In the present work, 5% of ZrO2 particulate by weight have been added to prepare Al/ZrO2(p)-MMC by stir casting techniques. Central composite design (CCD) of response surface methodology (RSM) considering full factorial approach for six process parameters has been used to design the experiment. Experiments have been performed in order to investigate the effect and optimization of input process parameters on performance measures like material removal rate and spark gap. The multi-optimization results obtained by initial parameters setting, response surface methodology and grey relational techniques have been compared and validated by confirmation experiments. The experiment results of performance characteristics have proved that newly developed MMC can be machined effectively by wire EDM.

Key words: WEDM; Material Removal Rate; Spark gap and Metal Matrix Composite.

## 1. Introduction

A composite can simply be defined as a combination of two or more dissimilar materials having a distinct interface between them such that the properties of the resulting material are superior to the individual constituting components (Bhargava, 2009). Metal Matrix Composites (MMC) have been so intensely researched over the past years that many new high strength to weight ratio materials have been prepared (Smith, 2004). Most of these materials have been developed for the aerospace industries, storage battery plates, satellite structures, antenna structure and high temperature structures (Kalpakjian and Stevan, 2000). In particulate reinforced composites, discrete, uniformly dispersed particles of a hard brittle material are surrounded by a softer more ductile matrix. Small particles of uniform size with proper orientation exhibit more strengthening effects. MMC can be manufactured by powder metallurgy route, diffusion bonding, co-continuous deformation, stir casting, deposition techniques, in-situ processing methods (Murthy *et al.*, 2005).

Many researchers have tried modern machining methods to machine the MMC and out of which wire electrical discharge machining (WEDM) emerged as an effective machining method. In the present work, parametric optimization of WEDM of Al/ZrO2(p) MMC is done using response surface methodology. WEDM is a complex machining process controlled by a large number of process parameters (Benedict, 1987; Boothroyd and Winston, 1989). The setting of the various process parameters required in the WEDM process, plays a crucial role in producing an optimal machining performance.

The parameter setting given by the manufacturers are only valid for the common steel grades so for advanced materials, parameters setting have to be optimized experimentally. Rozenek et al. (2001) experimentally investigated the effect of machining parameters on the machining feed rate and surface roughness during WEDM of metal matrix composites such as AlSi7Mg/SiC and AlSi7Mg/Al2O3 using brass wire. Yan et al. (2005) examined the WEDM of Al2O3p/6061Al composite. The experiment results indicated that the material removal rate, surface roughness and width of slit of cutting test material significantly depend on volume fraction of reinforcement (Al2O3 particles). Hewidy et al. (2005) modeled the WEDM parameters for Inconel 601 using

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response surface methodology for the performance characteristics such as metal removal rate, wear ratio, surface roughness using brass wire as wire electrode. Ramakrishnan and Karunamoorthy (2006) used zinc coated brass wire for WEDM of heat treated tool steel workpiece and obtained multi response optimization using Taguchi's robust design approach. Mahapatra and Patnaik (2006) used a 0.25 mm diameter zinc coated copper wire for a block of D2 tool steel workpiece in their experimental work and concluded that minimum wire tension gives maximum MRR but maximum wire tension gives maximum surface finish and minimum kerf. Chiang and Chang (2006) presented an effective approach for the optimization of the WEDM process of Al2O3 particle reinforced in Al 6061 alloy with multiple performance characteristics using pure copper as wire electrode. Surface removal rate and Surface roughness were investigated using grey relational analysis. Manna and Bhattacharyya (2006) used Taguchi and Gauss elimination method for the parametric optimization of aluminium reinforced silicon carbide metal matrix composite and used brass wire in WEDM. Effect of machining parameters on machining performance criteria such as metal removal rate, surface roughness, gap current, and spark gap were studied. Saha, Singha and Pal (2008) analyzed the wire electrical discharge machining of tungsten carbide cobalt composite using uncoated brass wire. Patil and Brahmankar (2010) experimentally investigated the effect of electrical as well as non-electrical machining parameters on performance in WEDM of metal matrix composite (Al/Al2O3p). Reinforcement percentage, current and on-time was found to have significant effect on cutting rate, surface finish and kerf width separately. Garg et al. (2010) conducted a review of research work in sinking EDM and WEDM on metal matrix composite materials. Most of the published work belongs to SiC reinforced metal matrix composites. Not so much work is reported Al2O3 reinforced and other MMC types. Patil and Brahmankar (2010) determined the material removal rate in wire electro-discharge machining of silicon carbide particulate reinforced aluminium matrix composites using dimensional analysis. The experimental results showed that increased percentage of ceramic particulates in the MMC results in declining of material removal rate. Kumar et al. (2011) investigated the wire electrical discharge machining of Al6063/SiCp composites. It was found that the increase in volume percentage of SiC results in declining of material removal rate and increase in surface roughness. Jangra et al. (2011) studied a digraph and matrix method to evaluate the machinability of tungsten carbide composite with WEDM. A methodology based on digraph and matrix method was proposed to evaluate the machinability of tungsten carbide in terms of material removal rate. Graph theoretic approach revealed that the machine tool had highest index value. Shah et al. (2011) investigated the effect of all critical WEDM parameters for the machining of tungsten carbide cobalt composites. It was found that the material thickness has little effect on the material removal rate and kerf but is significant factor in terms of surface roughness.

Literature survey on the WEDM of metal matrix composites reveals that no work has been reported on Al/ZrO2(p)-MMC so far. In the present work Al/ZrO2(p)-MMC has been prepared using Stir Casting technique. 5% of ZrO2 particulates by weight has been added to prepare Al/ZrO2(p)-MMC. Literature survey also reveals that diffused wire is not used for the WEDM of composites so in present work diffused wire has been used as wire electrode in experimentation. Comparison of performance measures using initial parameter setting, response surface methodology and grey relation analysis has also been presented in this paper.

## 2. Machining of Composite

Robofil-290 CNC wire EDM with brass coated (half hard) wire having 250 µm diameter has been used for experimentation. Figure 1 shows the photographic view for the WEDM of the workpiece. Performance of WEDM has been evaluated on the basis of material removal rate (MRR) and spark gap (SG). The MRR has been calculated utilizing the equation 1.

MRR = Mean cutting speed × Thickness of the workpiece in mm × Width of cut (mm)

$$= V_c t b \quad \text{mm}^3/\text{min.} \qquad \text{------------ (1)}$$

**Fig. 1 WEDM of Workpiece**

 

**Table: 1 Parameters, their Range, Coded Values and Real Values for the Experiment**

| Sr. No. | Parameters | Range/Value | Real values of the parameters corresponding to coded values | | | | |
|---|---|---|---|---|---|---|---|
| | | | -1.57 | -1 | 0 | 1 | +1.57 |
| 1 | PW | 0.36 to 1.14 µs | 0.36 | 0.5 | 0.75 | 1 | 1.14 |
| 2 | TBP | 4.61 to 23.39 µs | 4.61 | 8 | 14 | 20 | 23.4 |
| 3 | SPT | 0.12 to 0.60 µs | 0.12 | 0.2 | 0.35 | 0.5 | 0.6 |
| 4 | SCMRV | 11.52 to 58.48 volts | 11.52 | 20 | 35 | 50 | 58.5 |
| 5 | WFR | 4.87 to 11.13 m/min | 4.87 | 6 | 8 | 10 | 11.1 |
| 6 | WMT | 0.43 to 1.37daN | 0.43 | 0.6 | 0.9 | 1.2 | 1.4 |
| | | Constant parameters | | | | | |
| 1 | Work Piece Height | | 10.1 mm | | | | |
| 2 | Machining Voltage | | 80 volts | | | | |
| 3 | Ignition Pulse Current | | 8 units (1/2 A) | | | | |
| 4 | Maximum Feed Rate | | 10 units (73.2 micron/min.) | | | | |

**Table 2 Input Parameters Setting for the Experiment**

| RUN | PW | TBP | SPT | SCMRV | WFR | WMT | RUN | PW | TBP | SPT | SCMRV | WFR | WMT | RUN | PW | TBP | SPT | SCMRV | WFR | WMT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | -1 | -1 | -1 | -1 | -1 | -1 | **30** | 1 | -1 | 1 | 1 | 1 | -1 | **59** | -1 | 1 | -1 | 1 | 1 | 1 |
| **2** | 1 | -1 | -1 | -1 | -1 | -1 | **31** | -1 | 1 | 1 | 1 | 1 | -1 | **60** | 1 | 1 | -1 | 1 | 1 | 1 |
| **3** | -1 | 1 | -1 | -1 | -1 | -1 | **32** | 1 | 1 | 1 | 1 | 1 | -1 | **61** | -1 | -1 | 1 | 1 | 1 | 1 |
| **4** | 1 | 1 | -1 | -1 | -1 | -1 | **33** | -1 | -1 | -1 | -1 | -1 | 1 | **62** | 1 | -1 | 1 | 1 | 1 | 1 |
| **5** | -1 | -1 | 1 | -1 | -1 | -1 | **34** | 1 | -1 | -1 | -1 | -1 | 1 | **63** | -1 | 1 | 1 | 1 | 1 | 1 |
| **6** | 1 | -1 | 1 | -1 | -1 | -1 | **35** | -1 | 1 | -1 | -1 | -1 | 1 | **64** | 1 | 1 | 1 | 1 | 1 | 1 |
| **7** | -1 | 1 | 1 | -1 | -1 | -1 | **36** | 1 | 1 | -1 | -1 | -1 | 1 | **65** | -1.57 | 0 | 0 | 0 | 0 | 0 |
| **8** | 1 | 1 | 1 | -1 | -1 | -1 | **37** | -1 | -1 | 1 | -1 | -1 | 1 | **66** | 1.57 | 0 | 0 | 0 | 0 | 0 |
| **9** | -1 | -1 | -1 | 1 | -1 | -1 | **38** | 1 | -1 | 1 | -1 | -1 | 1 | **67** | 0 | -1.57 | 0 | 0 | 0 | 0 |
| **10** | 1 | -1 | -1 | 1 | -1 | -1 | **39** | -1 | 1 | 1 | -1 | -1 | 1 | **68** | 0 | 1.57 | 0 | 0 | 0 | 0 |
| **11** | -1 | 1 | -1 | 1 | -1 | -1 | **40** | 1 | 1 | 1 | -1 | -1 | 1 | **69** | 0 | 0 | -1.57 | 0 | 0 | 0 |
| **12** | 1 | 1 | -1 | 1 | -1 | -1 | **41** | -1 | -1 | -1 | 1 | -1 | 1 | **70** | 0 | 0 | 1.57 | 0 | 0 | 0 |
| **13** | -1 | -1 | 1 | 1 | -1 | -1 | **42** | 1 | -1 | -1 | 1 | -1 | 1 | **71** | 0 | 0 | 0 | -1.57 | 0 | 0 |
| **14** | 1 | -1 | 1 | 1 | -1 | -1 | **43** | -1 | 1 | -1 | 1 | -1 | 1 | **72** | 0 | 0 | 0 | 1.57 | 0 | 0 |
| **15** | -1 | 1 | 1 | 1 | -1 | -1 | **44** | 1 | 1 | -1 | 1 | -1 | 1 | **73** | 0 | 0 | 0 | 0 | -1.57 | 0 |
| **16** | 1 | 1 | 1 | 1 | -1 | -1 | **45** | -1 | -1 | 1 | 1 | -1 | 1 | **74** | 0 | 0 | 0 | 0 | 1.57 | 0 |
| **17** | -1 | -1 | -1 | -1 | 1 | -1 | **46** | 1 | -1 | 1 | 1 | -1 | 1 | **75** | 0 | 0 | 0 | 0 | 0 | -1.57 |
| **18** | 1 | -1 | -1 | -1 | 1 | -1 | **47** | -1 | 1 | 1 | 1 | -1 | 1 | **76** | 0 | 0 | 0 | 0 | 0 | 1.57 |
| **19** | -1 | 1 | -1 | -1 | 1 | -1 | **48** | 1 | 1 | 1 | 1 | -1 | 1 | **77** | 0 | 0 | 0 | 0 | 0 | 0 |
| **20** | 1 | 1 | -1 | -1 | 1 | -1 | **49** | -1 | -1 | -1 | -1 | 1 | 1 | **78** | 0 | 0 | 0 | 0 | 0 | 0 |
| **21** | -1 | -1 | 1 | -1 | 1 | -1 | **50** | 1 | -1 | -1 | -1 | 1 | 1 | **79** | 0 | 0 | 0 | 0 | 0 | 0 |
| **22** | 1 | -1 | 1 | -1 | 1 | -1 | **51** | -1 | 1 | -1 | -1 | 1 | 1 | **80** | 0 | 0 | 0 | 0 | 0 | 0 |
| **23** | -1 | 1 | 1 | -1 | 1 | -1 | **52** | 1 | 1 | -1 | -1 | 1 | 1 | **81** | 0 | 0 | 0 | 0 | 0 | 0 |
| **24** | 1 | 1 | 1 | -1 | 1 | -1 | **53** | -1 | -1 | 1 | -1 | 1 | 1 | **82** | 0 | 0 | 0 | 0 | 0 | 0 |
| **25** | -1 | -1 | -1 | 1 | 1 | -1 | **54** | 1 | -1 | 1 | -1 | 1 | 1 | **83** | 0 | 0 | 0 | 0 | 0 | 0 |
| **26** | 1 | -1 | -1 | 1 | 1 | -1 | **55** | -1 | 1 | 1 | -1 | 1 | 1 | **84** | 0 | 0 | 0 | 0 | 0 | 0 |
| **27** | -1 | 1 | -1 | 1 | 1 | -1 | **56** | 1 | 1 | 1 | -1 | 1 | 1 | **85** | 0 | 0 | 0 | 0 | 0 | 0 |
| **28** | 1 | 1 | -1 | 1 | 1 | -1 | **57** | -1 | -1 | -1 | 1 | 1 | 1 | **86** | 0 | 0 | 0 | 0 | 0 | 0 |
| **29** | -1 | -1 | 1 | 1 | 1 | -1 | **58** | 1 | -1 | -1 | 1 | 1 | 1 | | | | | | | |

 

Spark gap has been measured using profile projector PV-600A (make) having least count 0.001 mm. Table 1 shows the parameters, their range, coded values and real values for the experiment. Central composite design (CCD) of response surface methodology (RSM) has been used to design the experiment with the help of design of experiment (8.0 version) software. The coded values have been generated by CCD of RSM design considering six factors as input parameters.

## 3. Results and Discussions

Process performance characteristics such as material removal rate and spark gap have been used to analyze the effect of process parameters. Table 2 shows the parameter setting as per CCD design of RSM. Total 86 runs have been performed as shown in table 2.

### 3.1 Effect of process parameters on performance characteristics

Figure 2 represents the combined effect of pulse width and time between pulses on material removal rate (mm$^3$/min). From figure 2, it is clear that the material removal rate increases with the increase of pulse width whereas for the lower values of time between pulses, material removal rate increases with the increase of time between pulses but for the higher values of time between pulses, material removal rate decreases with the increase of time between pulses. Figure 3 represents the combined effect of servo control mean referance voltage and short pulse time on material removal rate. From figure 3, it is clear that the material removal rate increases with the increase of short pulse time whereas for the lower values of servo control mean referance voltage, material removal rate increases with the increase of servo control mean referance voltage but for the higher values of servo control mean referance voltage, material removal rate decreases with the increase of servo control mean referance voltage. This is because spark energy increases with the increase in pulse width and short pulse time or otherwise it decreases with increase in time between pulses and servo control mean referance voltage.

Figure 4 represents the combined effect of servo control mean referance voltage and wire feed rate on material removal rate. From figure 4, it is clear that wire feed rate has no significant effect on material removal rate. Figure 5 represents the combined effect of short pulse time and wire mechanical tension on spark gap (mm).

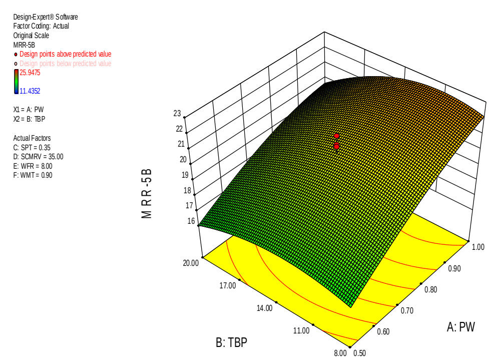


**Fig. 2 Effect of PW and TBP on MRR**

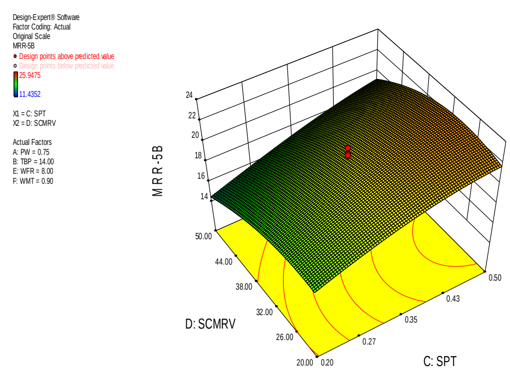


**Fig. 3 Effect of SPT and SCMRV on MRR**

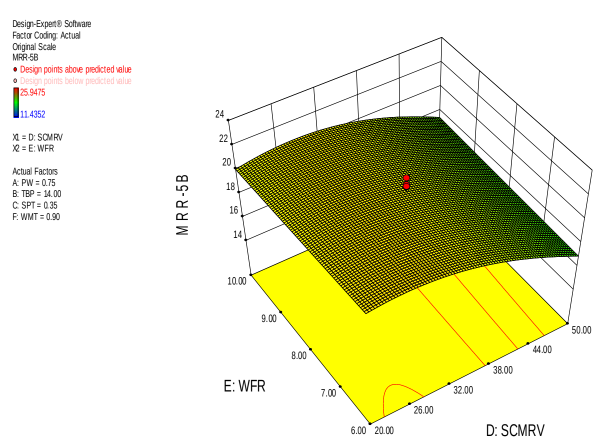


**Fig. 4 Effect of SCMRV and WFR on MRR**

 

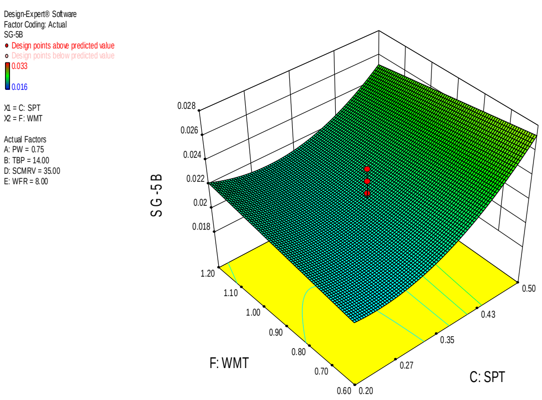


**Fig. 5 Effect of SPT and WMT on SG**

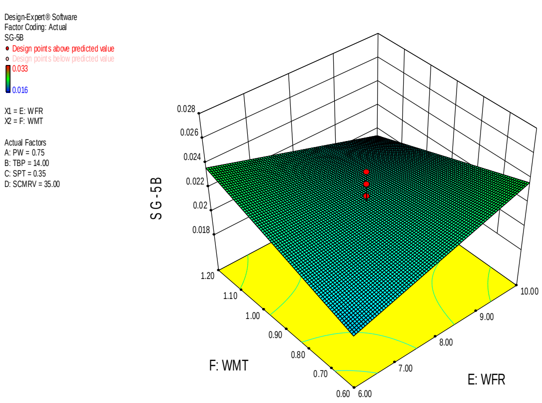


**Fig. 6 Effect of WFR and WMT on SG**

From figure 5, it is clear that spark gap increases with the increase of short pulse time whereas spark gap increases with the increase of time between pulses for the lower setting values of short pulse time but decreases with the increase of time between pulses for the higher setting values of short pulse time. Figure 6 represents the combined effect of wire feed rate and wire mechanical tension on spark gap. From figure 6, it is clear that spark gap increases with the increase of wire feed rate for the lower setting values of wire mechanical tension and decreases with the increase of wire feed rate for the higher setting values of wire mechanical tension. Similarly spark gap increases with the increase of wire mechanical tension for the lower setting values of wire feed rate and decreases with the increase of wire mechanical tension for the higher setting values of wire feed rate.This is because more spark energy increases larger crater formation hence more spark gap is produced.

## 3.2 Grey relational analysis

Multi-objective optimization theory using the grey relational analysis can be used for optimizing the parameters when only partial information is known. According to grey theory, all the known information is known as white information, all the unknown information is known as black information and partial information is known as Grey information (Deng, 1982; Deng, 1989). The grey relational analysis is simple, liable and efficient means multi-objective optimization of performance characteristics for machining Al/$ZrO_{2(p)}$ MMC. Response table shows the Grey relational grading which has been used to generate relationships among data sequences. The response table data shows the experimental results for the optimal machining parameters. The grey relational model determines relationship between two elements in a system and if the relationship higher, the grey relational grade is large.

### 3.2.1 Preprocessing data

The experimental results have been normalized and this data pre-processing step is known as the generation of grey relational data (Deng, 1982; Deng, 1989). The elements of each choice have been normalized using three different approaches such as larger-the-better, smaller-the-better and nominal-the-better. For the present investigation, material removal rate has been considered as larger-the-better characteristic and spark gap has been considered as smaller-the-better characteristics show by equation 2 and equation 3 respectively. Table 3 shows the preprocessed data for material removal rate and spark gap using equations 2 and 3 respectively.

$$X_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \qquad \text{................(2)}$$

$$X_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \qquad \text{.................(3)}$$

Where $X_i(k)$ is the value after grey relational generation; min $y_i$ (k) is smallest value of $y_i$ (k) for the $k^{th}$ response; max $y_i$ (k) is largest value of $y_i$ (k) for the $k^{th}$ response.

### 3.2.2 Calculation of grey relational coefficient

The grey relational coefficient can be calculated with the preprocessed data. Table 3 shows grey relational coefficient obtained by using equation 4.

$$\xi(X_{0i}, X_{ij}) = \frac{\Delta_{\min} + \xi\Delta_{\max}}{\Delta_{ij} + \xi\Delta_{\max}} \qquad \text{........(4)}$$

 

Where $\Delta_{ij} = \left| X_{oj} - X_{ij} \right|$; $\Delta_{min}$ = Min {$\Delta_{ij}$, i= 1, 2,........, m; j = 1,2,...........n};

$\Delta_{max}$ = Max {$\Delta_{ij}$, i= 1, 2,........, m; j = 1,2,...........n};

The distinguishing coefficient, ζ, is used to compensate the effect of the data series and is defined in the range 0-1. The value of ζ has been taken equal to 0.5.

### 3.2.3 Calculation of grey relational grade

The grey relational grade represents the levels of relationship between the reference sequence and the comparability sequence. Table 3 shows the grey relational grade obtained by using equation 5.

$$\gamma(X_{0j}, X_{ij}) = \frac{1}{n}\sum_{k=1}^{n} \xi(X_{0j}, X_{ij}) \quad ......(5)$$

**Table: 3 Preprocessed data, Grey relational coefficient and Grey relational grade.**

| S. No | Preprocessed data | | Grey relational coefficients | | Grey relational grade | S. No | Preprocessed data | | Grey relational coefficients | | Grey relational grade | S. No | Preprocessed data | | Grey relational coefficients | | Grey relational grade |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MRR | SG | Ξ MRR | ξ SG | γ | | MRR | SG | ξ MRR | ξ SG | γ | | MRR | SG | ξ MRR | ξ SG | γ |
| **1** | 0.1125 | 1 | 0.8163 | 0.3333 | 0.5623 | **30** | 0.6144 | 0.1875 | 0.4487 | 0.7179 | 0.5916 | **59** | 0.0142 | 0.875 | 0.9724 | 0.4158 | 0.6708 |
| **2** | 0.5381 | 0.75 | 0.4817 | 0.5202 | 0.4681 | **31** | 0.2798 | 0.3125 | 0.6412 | 0.637 | 0.6405 | **60** | 0.1231 | 0.875 | 0.8025 | 0.4352 | 0.5926 |
| **3** | 0.2693 | 0.9375 | 0.6499 | 0.4231 | 0.5095 | **32** | 0.575 | 0.0625 | 0.4651 | 0.6473 | 0.625 | **61** | 0.4493 | 0.9375 | 0.5267 | 0.4831 | 0.4646 |
| **4** | 0.5508 | 0.75 | 0.4758 | 0.4249 | 0.4413 | **33** | 0.215 | 0.5625 | 0.6993 | 0.3959 | 0.5673 | **62** | 0.7468 | 0.625 | 0.401 | 0.8766 | 0.53 |
| **5** | 0.3038 | 0.5 | 0.622 | 0.4395 | 0.5481 | **34** | 0.5557 | 0.1875 | 0.4736 | 0.5521 | 0.5631 | **63** | 0.3094 | 0.6875 | 0.6178 | 0.6366 | 0.5712 |
| **6** | 0.7739 | 0.3125 | 0.3925 | 0.5196 | 0.4833 | **35** | 0.2714 | 0.8125 | 0.6482 | 0.44 | 0.5241 | **64** | 0.4741 | 0.4375 | 0.5133 | 0.5853 | 0.5389 |
| **7** | 0.3992 | 0.625 | 0.556 | 0.4816 | 0.5088 | **36** | 0.5377 | 0.3125 | 0.4818 | 0.4519 | 0.5122 | **65** | 0.2168 | 1 | 0.6976 | 0.4664 | 0.5383 |
| **8** | 0.7881 | 0.5625 | 0.3882 | 0.8193 | 0.5167 | **37** | 0.3667 | 0.3125 | 0.5769 | 0.4831 | 0.5689 | **66** | 1 | 0.5625 | 0.3333 | 0.9096 | 0.5117 |
| **9** | 0.0827 | 1 | 0.8581 | 0.6892 | 0.6715 | **38** | 0.7604 | 0.125 | 0.3967 | 0.5379 | 0.5387 | **67** | 0.8395 | 0.3125 | 0.3733 | 0.9871 | 0.5904 |
| **10** | 0.2312 | 0.75 | 0.6838 | 0.7665 | 0.6297 | **39** | 0.5233 | 0.4375 | 0.4886 | 0.5675 | 0.522 | **68** | 0.2218 | 0.9375 | 0.6927 | 0.392 | 0.5226 |
| **11** | 0.0074 | 1 | 0.9855 | 0.641 | 0.7208 | **40** | 0.7205 | 0.25 | 0.4097 | 0.7672 | 0.5677 | **69** | 0.3133 | 0.625 | 0.6148 | 0.4912 | 0.5406 |
| **12** | 0.1373 | 0.875 | 0.7846 | 0.4781 | 0.5946 | **41** | 0.1566 | 0.5 | 0.7615 | 0.5861 | 0.6555 | **70** | 0.8196 | 0.375 | 0.3789 | 0.8208 | 0.5399 |
| **13** | 0.2445 | 0.625 | 0.6716 | 0.7589 | 0.636 | **42** | 0.2437 | 0.25 | 0.6723 | 0.7621 | 0.7023 | **71** | 0.5841 | 0.6875 | 0.4612 | 0.5868 | 0.4808 |
| **14** | 0.5596 | 0.6875 | 0.4719 | 0.8365 | 0.5486 | **43** | 0 | 0.625 | 1 | 0.4147 | 0.7148 | **72** | 0.2828 | 0.875 | 0.6387 | 0.5505 | 0.5413 |
| **15** | 0.2246 | 0.625 | 0.6901 | 0.4235 | 0.5614 | **44** | 0.1113 | 0.5625 | 0.818 | 0.4854 | 0.6496 | **73** | 0.541 | 0.4375 | 0.4803 | 0.6971 | 0.5501 |
| **16** | 0.4527 | 0.75 | 0.5248 | 0.5538 | 0.4978 | **45** | 0.3184 | 0.1875 | 0.6109 | 0.7068 | 0.6732 | **74** | 0.6602 | 0.875 | 0.431 | 0.8358 | 0.511 |
| **17** | 0.1209 | 0.875 | 0.8053 | 0.4041 | 0.5862 | **46** | 0.6422 | 0.25 | 0.4378 | 0.8373 | 0.5997 | **75** | 0.5521 | 0.4375 | 0.4752 | 0.8237 | 0.5792 |
| **18** | 0.5881 | 0.4375 | 0.4595 | 0.5109 | 0.493 | **47** | 0.2979 | 0.5 | 0.6266 | 0.6711 | 0.6083 | **76** | 0.6584 | 1 | 0.4316 | 0.4917 | 0.4159 |
| **19** | 0.2466 | 0.8125 | 0.6697 | 0.4237 | 0.5307 | **48** | 0.4149 | 0.375 | 0.5465 | 0.5995 | 0.5701 | **77** | 0.6405 | 0.75 | 0.4384 | 0.6419 | 0.4771 |
| **20** | 0.5002 | 0.5625 | 0.4999 | 0.4134 | 0.4713 | **49** | 0.1594 | 0.8125 | 0.7583 | 0.385 | 0.5646 | **78** | 0.6875 | 0.875 | 0.4211 | 0.5743 | 0.4408 |
| **21** | 0.3104 | 0.25 | 0.617 | 0.4288 | 0.5903 | **50** | 0.5082 | 0.5 | 0.4959 | 0.4239 | 0.4803 | **79** | 0.6498 | 0.8125 | 0.4348 | 0.6524 | 0.4723 |
| **22** | 0.7528 | 0 | 0.3991 | 0.5196 | 0.5871 | **51** | 0.1251 | 0.8125 | 0.7998 | 0.3875 | 0.5856 | **80** | 0.5294 | 0.8125 | 0.4857 | 0.5917 | 0.4822 |
| **23** | 0.4632 | 0.3125 | 0.5191 | 0.4927 | 0.5416 | **52** | 0.3758 | 0.6875 | 0.5709 | 0.4149 | 0.4924 | **81** | 0.6046 | 0.6875 | 0.4526 | 0.641 | 0.4901 |
| **24** | 0.8821 | 0 | 0.3618 | 0.6313 | 0.5955 | **53** | 0.4157 | 0.5 | 0.546 | 0.4192 | 0.5045 | **82** | 0.522 | 0.75 | 0.4892 | 0.6379 | 0.5012 |
| **25** | 0.13 | 0.8125 | 0.7937 | 0.5014 | 0.6111 | **54** | 0.8512 | 0.4375 | 0.3701 | 0.5196 | 0.4498 | **83** | 0.5404 | 0.5625 | 0.4806 | 0.5864 | 0.5048 |
| **26** | 0.2255 | 0.8125 | 0.6892 | 0.7627 | 0.625 | **55** | 0.3254 | 0.5625 | 0.6058 | 0.4973 | 0.5455 | **84** | 0.5842 | 0.625 | 0.4612 | 0.5505 | 0.4786 |
| **27** | 0.018 | 0.875 | 0.9653 | 0.5956 | 0.7122 | **56** | 0.6739 | 0.25 | 0.4259 | 0.4834 | 0.5052 | **85** | 0.5947 | 0.75 | 0.4567 | 0.6261 | 0.4822 |
| **28** | 0.0723 | 0.9375 | 0.8736 | 0.4909 | 0.6352 | **57** | 0.1783 | 0.875 | 0.7371 | 0.4149 | 0.5555 | **86** | 0.6405 | 0.875 | 0.4384 | 1 | 0.5557 |
| **29** | 0.2843 | 0.3125 | 0.6375 | 0.6428 | 0.6401 | **58** | 0.3909 | 0.8125 | 0.5612 | 0.5868 | 0.5181 | | | | | | |

**Table: 4 Response Table**

| Parameter | Symbol used | Level 1 (-1.57) | Level 2 (-1) | Level 3 (0) | Level 4 (1) | Level 5 (1.57) | Max-Min | Order |
|---|---|---|---|---|---|---|---|---|
| PW | A | 0.5383 | **0.5896*** | 0.50784 | 0.55046 | 0.51172 | 0.08176 | 4 |
| TBP | B | **0.5904*** | 0.56901 | 0.50469 | 0.57105 | 0.52255 | 0.0857 | 3 |
| SPT | C | 0.54057 | **0.5816*** | 0.50632 | 0.55846 | 0.53993 | 0.07528 | 5 |
| SCMRV | D | 0.48083 | 0.52893 | 0.50923 | **0.61113*** | 0.54135 | 0.1303 | 2 |
| WFR | E | 0.55014 | **0.57612*** | 0.50729 | 0.56394 | 0.51099 | 0.06884 | 6 |
| WMT | F | **0.57921*** | 0.57421 | 0.51059 | 0.56585 | 0.41592 | 0.16329 | 1 |

**Table 5: Results of Confirmation Experiment and Comparison between Initial Parameter Setting, Response Surface Methodology and Grey Relational Analysis**

| Sr. No. | Initial parameter setting | Method utilized for optimization | Optimal setting | Results (Experimental) | | % Change | |
|---|---|---|---|---|---|---|---|
| | | | | MRR | SG | MRR | SG |
| 1. | $A_2B_2C_2D_2E_2F_2$ | ----- | ----- | 19.6917 | 0.02 | ----- | ----- |
| 2. | ----- | Response Surface Methodology | A=1.00; B=16.19; C=0.44; D=21.80; E=6.00; F=0.60 | 22.4433 | 0.0198 | 13.97 | 1.0 |
| 3. | ----- | Grey Relational Analysis | $A_2$=0.5; $B_4$=20; $C_2$=0.3; $D_4$=50; $E_4$=10; $F_2$=0.6 | 23.346 | 0.021 | 18.55 | 5.0 |

**Table 6 Comparison of Performance Measures using Brass and Diffused Wire Electrode**

| S. NO. | Optimum Value of Responses | | | | % Change | |
|---|---|---|---|---|---|---|
| | Brass Wire Electrode | | Diffused Wire Electrode | | | |
| | MRR max | SG min | MRR max | SG min | MRR max | SG min |
| 1 | 22.337 | 0.02 | 23.346 | 0.021 | 4.51 | 5.0 |

### 3.2.4 Response Table for grey relational grade

Table 4 shows how the effect of each machining parameters and the order of all machining parametric levels has been determined. The table includes information on the magnitude of impacts of wire EDM cutting parameters from greatest to least impact for each of the following factors: wire mechanical tension, servo control mean reference voltage, time between pulses, pulse width, short pulse time and wire feed rate. Based on response table 4, the optimal level of machining parameters comes out to be as $A_2$, $B_1$, $C_2$, $D_4$, $E_2$ and $F_1$ for performance characteristics material removal rate (MRR) and spark gap (SG) considering together for multi response optimization. That is, the optimal machining conditions for multi response optimization are pulse width of 0.5 µs, time between pulses of 4.61 µs, short pulse time of 0.3 µs, servo control mean reference voltage of 50 volts, wire feed rate of 6 m/min and wire mechanical tension of 0.43 daN.

## 4. Comparison of performance Measures and Confirmation Experiment

Table 5 shows the comparison between initial parameter setting, multi-optimization result obtained from response surface methodology and multi-optimization result obtained from grey relational analysis. It also shows the results of the confirmation test performed to validate the results obtained from the grey relational analysis. The percentage change in the optimal setting obtained by response surface methodology as compared to initial parameters setting comes out to be 13.97 and 1% in the material removal rate and spark gap respectively whereas the percentage change in the optimal setting obtained by grey relational analysis is 18.55 and 5% in the material removal rate and spark gap respectively.

 

Comparison between material removal rate (MRR) and spark gap (SG) using brass and diffused wire electrode is shown in table 6. The percentage increase in MRR while using diffused wire electrode as compared to brass wire electrode comes out to be 4.51% and percentage increase in SG comes out to be 5.0%.

## 5. Conclusions

i. Based on the experimental results during WEDM of Al /$ZrO_{2(p)}$ metal matrix composite (MMC), the following points are concluded and listed below:

ii. Material removal rate increases with the increase of pulse width and short pulse time whereas for the lower values of time between pulses and servo control mean referance voltage, material removal rate increases with the increase of time between pulses and servo control mean referance voltage but for the higher values of time between pulses and servo control mean referance voltage, material removal rate decreases with the increase of time between pulses and servo control mean referance voltage respectively. Wire feed rate has no significant effect on material removal rate.

iii. Spark gap increases with the increase of short pulse time whereas spark gap increases with the increase of time between pulses, wire feed rate and wire mechanical tension for the lower setting values of short pulse time, wire mechanical tension and wire feed rate respectively but decreases with the increase of time between pulses, wire feed rate and wire mechanical tension for higher setting values of short pulse time, wire mechanical tension and wire feed rate respectively.

iv. The optimal machining conditions for multi response optimization are as follows: pulse width of 0.5 μs, time between pulses of 4.61 μs, short pulse time of 0.3 μs, servo control mean reference voltage of 50 volts, wire feed rate of 6 m/min and wire mechanical tension of 0.43 daN.

v. The higher value of material removal rate is 23.346 $mm^3$/min and minimum value for spark gap is 0.021 mm indicate that the Al/$ZrO_{2(p)}$ metal matrix composite (MMC) can be machined effectively by WEDM.

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