

# Optimization of Dry Electrical Discharge Machining of High Speed Steel Using Grey-relational Analysis

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**Abstract**—Dry electrical discharge machining (DEDM) is considered as a green format of the conventional oil dielectric EDM where a gas is used as the dielectric medium. This paper details experimental results when DEDM of high speed steel workpieces using multi-response optimization. Experimental trials were performed to investigate the influence of current, pulse on-time, duty factor, gas pressure and spindle rotational speed on material removal rate (MRR), surface roughness (Ra), and radial over cut (ROC). Grey relational analysis (GRA) based on Taguchi approach was employed for multi-objective optimization of DEDM responses. Confirmation trials were subsequently conducted and results showed that process responses can be successfully optimized using GRA. Results showed that current, duty factor and air pressure were found to be statistically significant factors at 90% confidence level, with percentage contribution ratios (PCRs) of 72.8%, 4.3%, and 3.7%, respectively. Micro pores and minor surface cracks were visible in the majority of specimens.

**Keywords**—Dry EDM, grey-relational analysis, multi-objective optimization.

## I. INTRODUCTION

ELECTRICAL discharge machining (EDM) is a well-known machining process that is capable of cutting hard to machine materials and is being widely used over the last few decades. It is used by many industries in order to make moulds and dies and complex structures of difficult-to-cut tungsten carbide and its composites [1]. A different format of EDM known as dry electrical discharge machining (DEDM) is developed employing a gas as the dielectric replacing the conventional oil-based dielectric. One of the first attempts to use the gas in dielectric mediums was supplying oxygen gas in to the discharge gap when a water-based dielectric has been used [2]. The attempt showed a higher MRR in comparison with the conventional EDM, then in 1997, Kunieda et al. used the oxygen as the only dielectric medium [3]. This gas passes through a hollow electrode at pressure of 0.5 MPa. Hence, it serves as the standard dielectrics to flush debris particles away, cool discharge region and recovery of dielectric strength for the next spark. Due to the lower viscosity of gas dielectrics used in DEDM compared with liquid dielectrics used in conventional

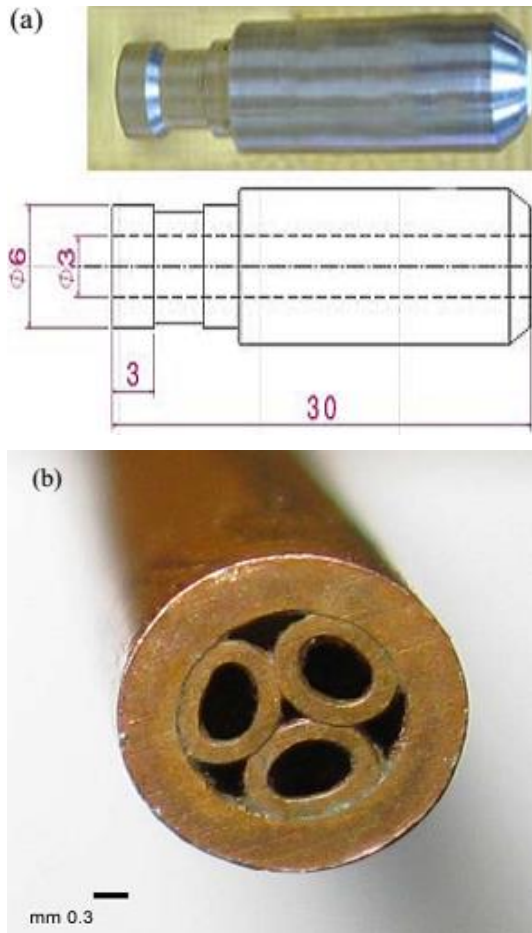
EDM, for example, the dynamic viscosity ratio of air to the water is 0.018 [4], plasma channel is able to grow faster, but the concentration of thermal energy decreases. Therefore, rotation or planetary motion of pipe electrode is employed to improve the plasma channel stability and also to enhance the flushing condition [3]. Benefits of DEDM include the lower tool wear rate (TWR), good surface finish and less surface and subsurface damages in comparison with conventional EDM [5]. As a result, DEDM has the potential to be used in a wide range of industrial applications such as aerospace, maritime and automotive [6]. The challenge of optimising several responses when using EDM is not uncommon due to the high number of variables affecting the process. Additionally, the relations between process control variables are complex and sometimes unclear. For this reason, numerous studies were conducted using several techniques including but not limited to multi-objective optimisation approach for conventional EDM, while optimisation of DEDM is deemed tenuous. Such complex and unclear scenarios are conventionally named “Grey systems” that give poor, incomplete and uncertain information, and can be studied effectively using Grey relational analysis (GRA) [7].

Single objective optimisation and conventional multi-objective optimisation methods such as weighted aggregation techniques were found problematic in solving uncertain, multi-input and discrete data related to the Grey systems. GRA on the other hand was first introduced in 1989 by Deng [8] to solve grey engineering problems and found to be efficient in tackling such problems. GRA was successfully used to optimise laser and WEDM machining processes where multiple performance responses were investigated against several process control variables [9]. GRA articulates such systems by combining values for all responses into a single representative value and subsequently optimising the system as a single performance characteristic [10]. The GRA was also found beneficial when used for optimising multi-objective functions of various EDM processes [11] with considerable improvement in responses when confirmation trials were performed at optimum levels of process conditions advocated by GRA. On the other hand, limited research for optimising DEDM control variables against multiple responses is available. Therefore, this paper aims to investigate the use of Grey

relational analysis based on Taguchi approach when DEDM of steel alloys.

## II. EXPERIMENTAL SETUP

Experiments were performed using a bespoke Tehran Ekram 304-H die sinking EDM machine. An electromotor employed with inverter was fitted to supply the rotating motion of the main spindle which accommodates the tool (electrode). This rotation was subsequently transferred to the spindle using pulley and belt drive. A gas inlet was mounted on the freewheeling cylinder. A ceramic pipe guide (**Figure 1(a)**) was used to prevent electrode limping during the penetration. **Figure 1(b)** shows the copper electrode of 3 mm diameter and has three eccentric holes.



**Figure 1 (a) Ceramic pipe guide (All dimensions are in mm)**  
**(b) Cross section of the 3.0 mm diameter three-channel copper pipe electrode**

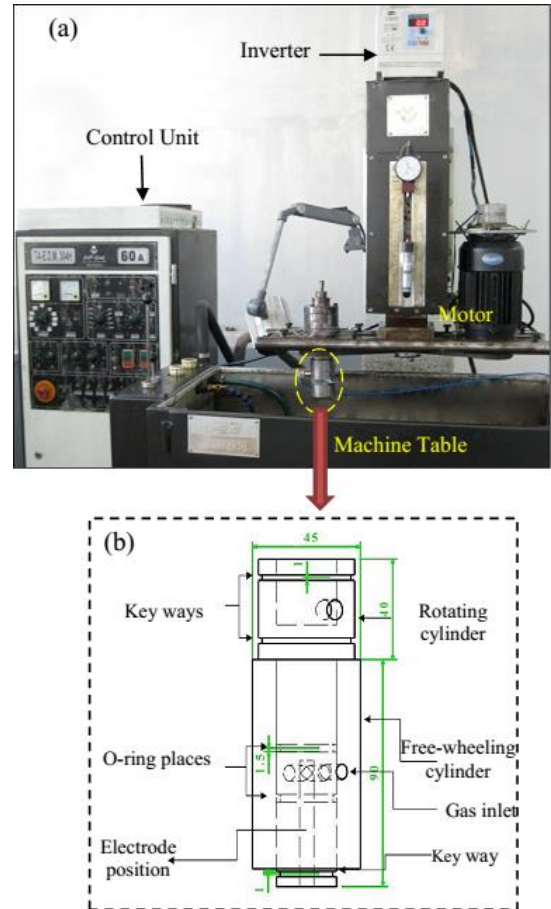
The bespoke experimental setup used is shown in **Figure 2(a)** while **Figure 2(b)** details the modification introduced to the original setup. The modification included two keys mounted on the top of the rotating cylinder in order to hold the pulley which was used to transfer rotary motion. The key mounted on the bottom of the key way was used to hold a freewheeling cylinder. High speed steel M35 series (0.94% C) was used as the workpiece material. Atmospheric air under different pressures was used as dielectric medium. Each experiment was replicated

three times and the average was then computed. Following the experimentation, MRR was calculated according to (1).

$$MRR(\text{mm}^3 / \text{min}) = \frac{W_2 - W_1}{\rho_w \times t} \times 1000 \quad (1)$$

where  $W_1$  and  $W_2$  were workpiece mass (grams) before and after machining, respectively,  $\rho_w$  is workpiece density in  $\text{gram}/\text{cm}^3$  and  $t$  is machining time (minutes).

Radial overcut “defined as the difference between the cut hole diameter hole and electrode diameter in radial direction” was measured using a Mitutoyo coordinate measuring machine having  $0.1 \mu\text{m}$  resolution. Average surface roughness (Ra) was evaluated using Mahr PS-1 instrument. Additionally, images for the machined surfaces were taken using SEM to evaluate the machined surface integrity.



**Figure 2 (a) Bespoke DEDM experimental set up and**  
**(b) Schematic of the modified mechanism**  
**(All dimensions are in mm)**

## III. MULTI-RESPONSE OPTIMIZATION USING GREY RELATIONAL ANALYSIS AND TAGUCHI METHOD

Taguchi fractional factorial design of L27 orthogonal array was employed. Five process control variables, each at 3 levels, including current (I), pulse on-time ( $T_{on}$ ), duty factor (D), gas pressure (P) and spindle rotation speed (N) were investigated

(detailed in TABLE I). The key process responses were material removal rate (MRR), radial overcut (ROC) and average surface roughness (Ra) that were critically selected according to literature of EDM process as well as preliminary explanatory experiments preceded the main stream testing. Tool wear rate as a process response was excluded from this investigation as negligible electrode wear was observed during the experimentation. Analysis of variance was then carried out using Minitab 16.2 to reveal the statistically significant parameters on process responses and Grey relational grades.

**TABLE I PROCESS CONTROL VARIABLES AND THEIR CORRESPONDING LEVELS**

| Variable                           | Level |     |     |
|------------------------------------|-------|-----|-----|
|                                    | 1     | 2   | 3   |
| Current, I (A)                     | 15    | 30  | 45  |
| Pulse on time, $T_{on}$ ( $\mu$ s) | 50    | 200 | 450 |
| Duty factor, D                     | 33    | 66  | 86  |
| Air pressure, P (bar)              | 1     | 2   | 3   |
| Spindle rotation speed, N (rpm)    | 150   | 400 | 650 |

In order to analyze responses, two types of response analyses are mainly used: S/N (signal-to-noise) ratio analysis and analysis of responses means. S/N ratio analysis is typically used when the iteration and number of trials are large in a way that the response noises affect the analysis. Therefore the responses were initially converted to the S/N ratios according to their characteristics, the-higher-the-better (HB) for MRR and Grey Grades and the-lower-the-better (LB) for ROC and Ra. The conversion to S/N were taken place using (2) and (3).

$$HB:S/N = -10 \log \left( \frac{\sum_{i=1}^N \frac{1}{x_i^2}}{n} \right) \quad (2)$$

$$LB:S/N = -10 \log \left( \frac{\sum_{i=1}^N x_i^2}{n} \right) \quad (3)$$

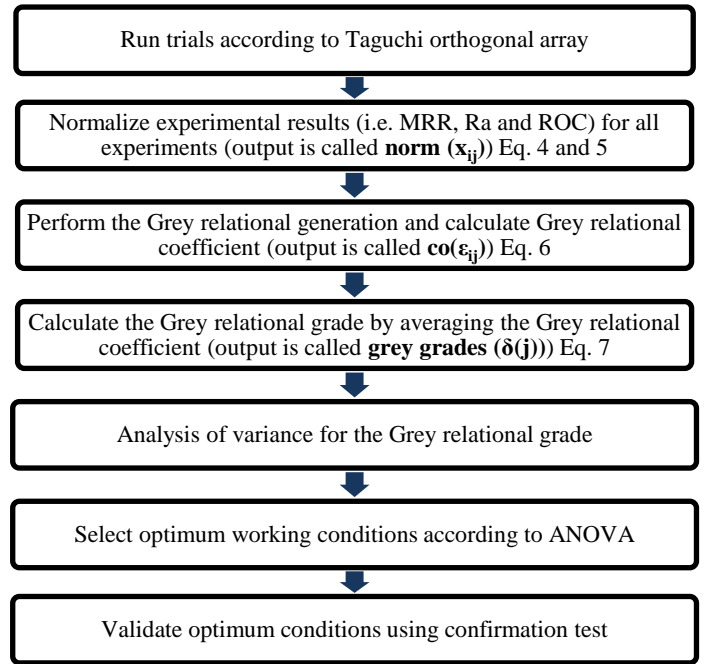
In this research, analysis of variance (ANOVA) are performed for both of the responses means and S/N ratio values. The high similarity in the trends obtained from both analyses indicated that the noises rarely affect responses. In the results and discussion section, the main effects plots and ANOVA table are presented only for the means.

Not uncommonly, conditions for higher MRR usually lead to higher Ra and ROC which is contradictory to the requirements [11]. Grey relational analysis is considered as a suitable technique to mitigate such adverse effects when optimising such complex system. GRA was performed in this study through the steps shown in **Figure 3** and then the steps described as follows:

$$x_{ij} = \frac{\max y_{ij} - y_{ij}}{\max y_{ij} - \min y_{ij}} \quad \text{for LB characteristics} \quad (4)$$

$$x_{ij} = \frac{y_{ij} - \min y_{ij}}{\max y_{ij} - \min y_{ij}} \quad \text{for HB characteristics} \quad (5)$$

where  $x_{ij}$  is the response normalised value (i.e. number between 0 and 1), where  $i$  is the experiment number (in this work  $i = 1, \dots, 27$ ) and  $j$  is the response number (in this work  $j = 1, 2, 3$  for the three investigated responses MRR, Ra and ROC)  $\min y_{ij}$  and  $\max y_{ij}$  are the smallest and largest value for  $j_{th}$  response respectively,



**Figure 3 Flow chart of GRA process**

Ideal situation (higher MRR and lower Ra and ROC) is highest value of  $x_{ij}$  for each  $j$  regardless the characteristic type. Consequently the Grey relational coefficient is calculated using (6):

$$\xi_{ij} = \frac{\Delta_{\min} + \psi \Delta_{\max}}{\Delta_{0i}(j) + \psi \Delta_{\max}} \quad (6)$$

where  $\Delta_{0i}(j) = |x_{0j} - x_{ij}|$ ,  $x_{0j}$  is the absolute value for each normalized response,  $0 < \psi < 1$  is the distinguishing and resolution coefficient. An average value of  $\psi$  (0.5) was used as suggested by the literature [12], [13].

The last step is to calculate the Grey relational grades as follows:

$$\delta(j) = \frac{1}{m} \sum_{i=1}^m \xi_{ij}, \quad m = 3 \quad (\text{number of responses}) \quad (7)$$

TABLE II L27 OA AND GREY RELATIONAL ANALYSIS COEFFICIENTS/GRADES

| No | I  | T <sub>on</sub> | D  | P | N   | MRR<br>(mm <sup>3</sup> /min) | Ra<br>(μm) | ROC<br>(mm) | MRR<br>norm | Ra<br>norm | ROC<br>norm | MRR<br>co | Ra<br>co | ROC<br>co | Grey<br>grade | S/N<br>ratio |
|----|----|-----------------|----|---|-----|-------------------------------|------------|-------------|-------------|------------|-------------|-----------|----------|-----------|---------------|--------------|
| 1  | 15 | 50              | 33 | 1 | 150 | 0.412                         | 2.949      | 0.105       | 0.000       | 0.922      | 0.790       | 0.333     | 0.865    | 0.704     | 0.634         | -3.95        |
| 2  | 15 | 50              | 66 | 2 | 400 | 0.577                         | 2.711      | 0.053       | 0.034       | 0.970      | 0.969       | 0.341     | 0.944    | 0.942     | 0.742         | -2.59        |
| 3  | 15 | 50              | 86 | 3 | 650 | 0.692                         | 2.903      | 0.088       | 0.057       | 0.931      | 0.849       | 0.347     | 0.879    | 0.768     | 0.665         | -3.55        |
| 4  | 15 | 200             | 33 | 2 | 400 | 1.107                         | 2.688      | 0.093       | 0.142       | 0.975      | 0.832       | 0.368     | 0.952    | 0.748     | 0.690         | -3.23        |
| 5  | 15 | 200             | 66 | 3 | 650 | 1.107                         | 2.796      | 0.073       | 0.142       | 0.953      | 0.901       | 0.368     | 0.915    | 0.835     | 0.706         | -3.02        |
| 6  | 15 | 200             | 86 | 1 | 150 | 1.217                         | 3.318      | 0.097       | 0.164       | 0.847      | 0.817       | 0.374     | 0.766    | 0.732     | 0.624         | -4.10        |
| 7  | 15 | 450             | 33 | 3 | 650 | 0.977                         | 2.565      | 0.080       | 0.115       | 1.000      | 0.875       | 0.361     | 1.000    | 0.800     | 0.720         | -2.85        |
| 8  | 15 | 450             | 66 | 1 | 150 | 0.879                         | 3.218      | 0.049       | 0.095       | 0.868      | 0.982       | 0.356     | 0.791    | 0.966     | 0.704         | -3.05        |
| 9  | 15 | 450             | 86 | 2 | 400 | 1.407                         | 3.057      | 0.044       | 0.203       | 0.900      | 1.000       | 0.386     | 0.834    | 1.002     | 0.740         | -2.61        |
| 10 | 30 | 50              | 33 | 2 | 650 | 1.055                         | 3.249      | 0.058       | 0.131       | 0.861      | 0.951       | 0.365     | 0.783    | 0.910     | 0.686         | -3.27        |
| 11 | 30 | 50              | 66 | 3 | 150 | 1.160                         | 3.610      | 0.048       | 0.153       | 0.788      | 0.988       | 0.371     | 0.702    | 0.976     | 0.683         | -3.31        |
| 12 | 30 | 50              | 86 | 1 | 400 | 1.566                         | 3.895      | 0.069       | 0.236       | 0.730      | 0.914       | 0.395     | 0.650    | 0.853     | 0.633         | -3.98        |
| 13 | 30 | 200             | 33 | 3 | 150 | 2.420                         | 3.563      | 0.086       | 0.410       | 0.798      | 0.854       | 0.459     | 0.712    | 0.774     | 0.648         | -3.76        |
| 14 | 30 | 200             | 66 | 1 | 400 | 2.784                         | 4.066      | 0.064       | 0.484       | 0.696      | 0.931       | 0.492     | 0.622    | 0.879     | 0.664         | -3.55        |
| 15 | 30 | 200             | 86 | 2 | 650 | 3.480                         | 4.028      | 0.073       | 0.626       | 0.703      | 0.899       | 0.572     | 0.628    | 0.831     | 0.677         | -3.39        |
| 16 | 30 | 450             | 33 | 1 | 400 | 1.740                         | 3.924      | 0.133       | 0.271       | 0.725      | 0.692       | 0.407     | 0.645    | 0.619     | 0.557         | -5.09        |
| 17 | 30 | 450             | 66 | 2 | 650 | 1.827                         | 3.772      | 0.072       | 0.289       | 0.755      | 0.904       | 0.413     | 0.671    | 0.839     | 0.641         | -3.86        |
| 18 | 30 | 450             | 86 | 3 | 150 | 2.375                         | 4.294      | 0.116       | 0.401       | 0.649      | 0.752       | 0.455     | 0.588    | 0.668     | 0.570         | -4.88        |
| 19 | 45 | 50              | 33 | 3 | 400 | 2.375                         | 5.315      | 0.165       | 0.401       | 0.442      | 0.584       | 0.455     | 0.473    | 0.546     | 0.491         | -6.18        |
| 20 | 45 | 50              | 66 | 1 | 650 | 1.890                         | 6.259      | 0.127       | 0.302       | 0.251      | 0.713       | 0.417     | 0.400    | 0.636     | 0.484         | -6.30        |
| 21 | 45 | 50              | 86 | 2 | 150 | 2.537                         | 6.666      | 0.151       | 0.434       | 0.168      | 0.633       | 0.469     | 0.376    | 0.576     | 0.474         | -6.49        |
| 22 | 45 | 200             | 33 | 1 | 650 | 3.959                         | 6.230      | 0.257       | 0.724       | 0.257      | 0.264       | 0.644     | 0.402    | 0.405     | 0.484         | -6.31        |
| 23 | 45 | 200             | 66 | 2 | 150 | 4.510                         | 6.419      | 0.144       | 0.837       | 0.219      | 0.654       | 0.754     | 0.390    | 0.591     | 0.578         | -4.76        |
| 24 | 45 | 200             | 86 | 3 | 400 | 5.310                         | 6.608      | 0.228       | 1.000       | 0.180      | 0.366       | 1.000     | 0.379    | 0.441     | 0.607         | -4.34        |
| 25 | 45 | 450             | 33 | 2 | 150 | 3.157                         | 6.172      | 0.280       | 0.560       | 0.269      | 0.186       | 0.532     | 0.406    | 0.381     | 0.440         | -7.14        |
| 26 | 45 | 450             | 66 | 3 | 400 | 4.360                         | 6.143      | 0.181       | 0.806       | 0.274      | 0.528       | 0.720     | 0.408    | 0.514     | 0.548         | -5.23        |
| 27 | 45 | 450             | 86 | 1 | 650 | 4.381                         | 7.479      | 0.334       | 0.810       | 0.004      | 0.000       | 0.725     | 0.334    | 0.333     | 0.464         | -6.67        |

#### IV. RESULTS AND DISCUSSION

##### A. Taguchi design of experiment results

TABLE II shows the experimental plan (entitles 27 trials) in addition to results for the investigated responses (MRR, ROC and Ra). Main effects plots for individual key responses investigated in this research are shown in Figure 4. The preferred level for each process variable is identified with a circle. MRR can be maximized using high current (45A), moderate to high pulse-on time, high duty factor with limited effect of gas pressure and spindle speed. Surface roughness (Ra) was considerably influenced by the current with favourable results when lower current was used. This is obviously in contrast with preferred working conditions for greater MRR. Duty factor was also found to have a marginal effect on surface roughness and lower setting is preferred (33). All other control variables had very limited impact on surface roughness results which means adjusting them to improve the MRR is anticipated to not have a knock-on effect on Ra results. Smaller ROC can be achieved when lower to moderate current (15-30A) is used at

smaller T<sub>on</sub>, moderate levels of duty factor and gas pressure while very limited effect from changing the spindle rotational speed.

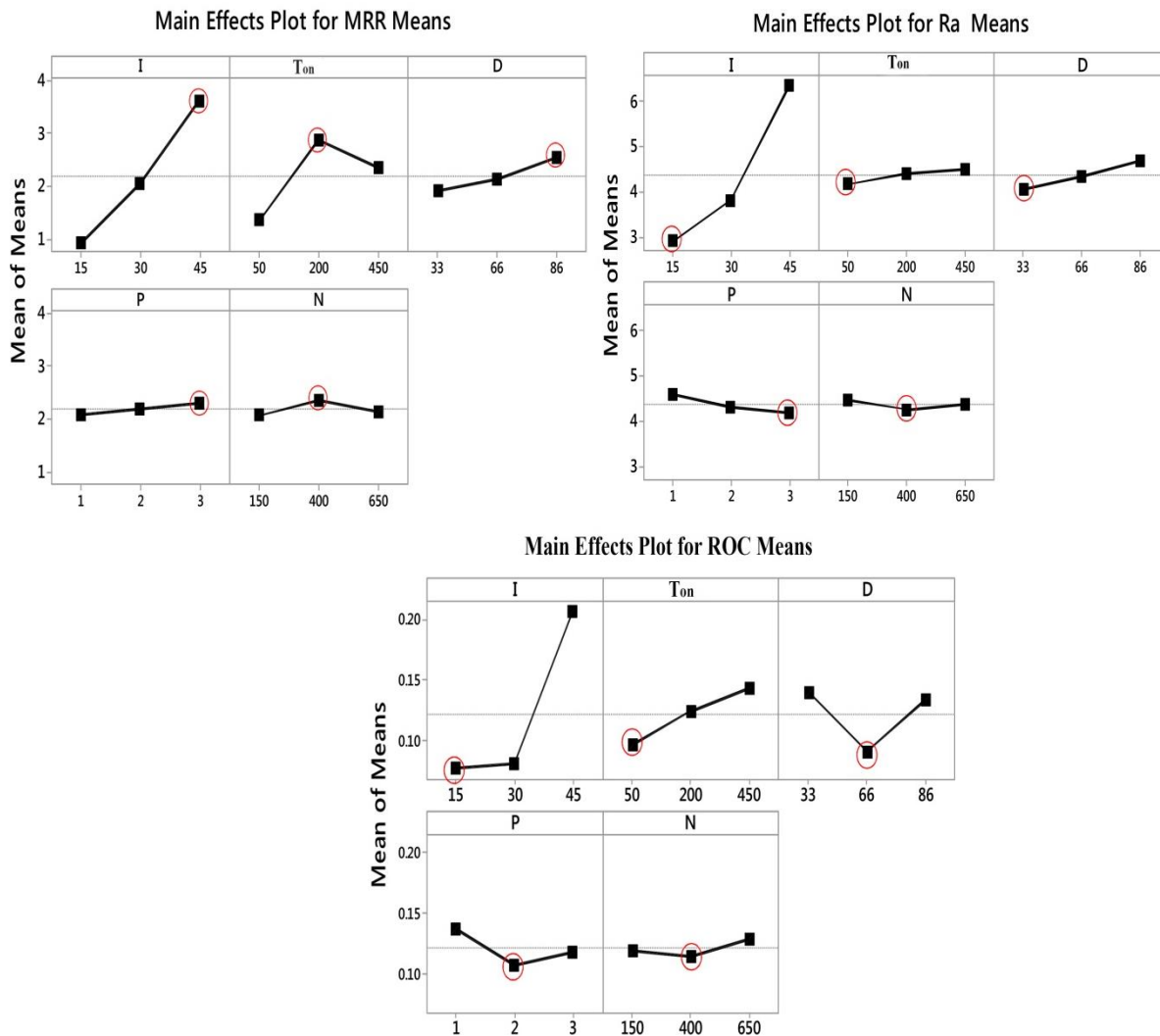
The optimum conditions obviously differ between responses, and selecting one set may result in discounting other responses from the analysis. Therefore, GRA was used to provide compromised optimum conditions that take into consideration all investigated responses. The data were subsequently processed to identify the collective optimum working conditions for DEDM of steel workpieces via calculating GRA for each run (procedure was detailed in Experimental Work section). The higher Grey relational grade for a certain experiment indicated that it was close to ideal/optimum situation (because the optimum conditions may not exist in the fractional factorial experimental design used in the research). In this study, experiment number 2 had the best multi-response characteristics with the highest Grey relational grade (0.742). This means working conditions used in experimental 2 (A1B1C2D2E2) were the best conditions only among 27 experiments conducted within the employed fractional factorial array (L27).

*B. Multi-objective optimization with GRA based Taguchi*

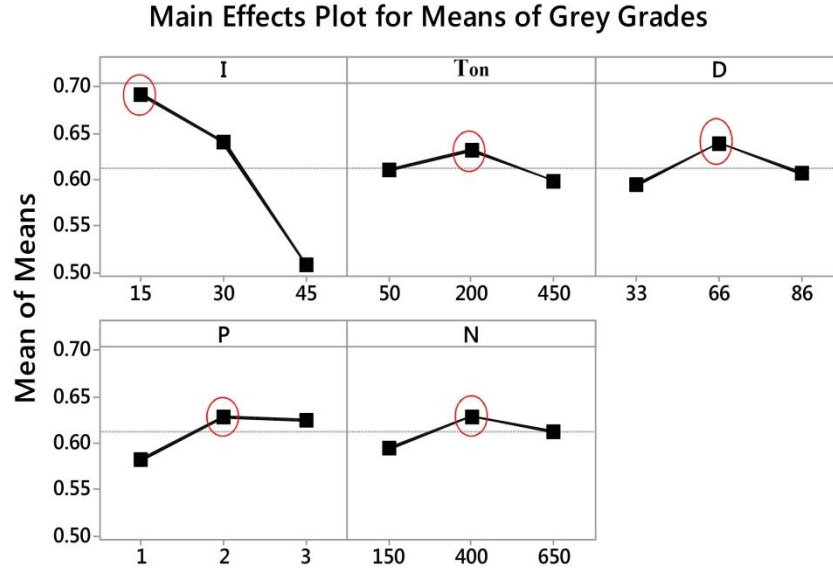
However, this set of working conditions may not present the absolute optimum situation (which can have greater GRA value) for all possible combinations (if a full factorial experimental design was employed), and therefore it would be called “initial best conditions” in this paper. This would be followed by another step to produce the most optimum conditions using ANOVA. In case of the new set of conditions is different, it would be called “optimum conditions” and a confirmation test would be required to verify that this set has better quality characteristics compared to the initial best conditions set by comparing the experimental results as well as the grey relational grade.

ANOVA results for the Grey relational grades mean values are shown in TABLE III. The significance of parameters was

evaluated by comparing p value by  $\alpha$  level of 0.05. According to ANOVA results, current “I” and air pressure (P) were found to be statistically significant at 95% confidence level ( $\alpha=0.05$ ). Current had also the highest Percentage contribution ratio (PCR) of 72.9%. The error was found to be statistically acceptable level of 15% which may indicate a less significance of the interactions between control variables. **Figure 5** shows the main effects plot for means of the grey relational grades. It was apparent that the discharge current had the highest contribution which was represented by the sharp slope of the Means. Higher current understandably helped to increase the material removal rate with a knock-on effect on the surface finish and perhaps the geometrical accuracy of the machined surface. In this case, lower current was proposed as the best/optimum level, which could be contributed to those two responses that had the lower-the-better characteristic.



**Figure 4 Main Effects Plots for Means of individual responses MRR, Ra and ROC (circles indicate the preferred level for optimum conditions/levels for each process control variable)**



**Figure 5 Main Effects Plot for Means of Grey relational grades**  
(circles indicate the preferred level for optimum conditions/levels for each process control variable)

**TABLE III ANOVA RESULTS FOR GREY RELATIONAL GRADE**

|                       | DF | SS      | MSS     | EXP SS  | F     | P      | PCR %       |
|-----------------------|----|---------|---------|---------|-------|--------|-------------|
| <b>I</b>              | 2  | 0.16213 | 0.08107 | 0.16052 | 50.29 | 0*     | <b>72.9</b> |
| <b>T<sub>on</sub></b> | 2  | 0.00491 | 0.00245 | 0.00329 | 1.52  | 0.248  | <b>1.5</b>  |
| <b>D</b>              | 2  | 0.00963 | 0.00482 | 0.00802 | 2.99  | 0.079  | <b>3.6</b>  |
| <b>P</b>              | 2  | 0.01216 | 0.00608 | 0.01055 | 3.77  | 0.045* | <b>4.8</b>  |
| <b>N</b>              | 2  | 0.00556 | 0.00278 | 0.00394 | 1.72  | 0.21   | <b>1.8</b>  |
| <b>Error</b>          | 16 | 0.02579 | 0.00161 |         |       |        | <b>15.4</b> |
| <b>Total</b>          | 26 | 0.22018 |         |         |       |        |             |

DF = Degrees of freedom      F = F-test value  
SS = Sum of squares            P = Probability  
Exp. SS = Expected sum of squares      PCR = Percent contribution ratio

\* Significant at the 5% level

### C. Optimum working conditions and confirmation testing

According to ANOVA results detailed in the previous section, the overall preferred working conditions were I=15 A, T<sub>on</sub>=200 μs, D=66, P=2 bar and N= 400 rpm (A1B2C2D2E2). Clearly, the optimised levels for each response alone differ from multi response GRA optimised levels. This is attributed to the variability of nature for each individual response (i.e. the-higher-the-better for MRR and the-lower-the-better for Ra and ROC). This deviated from the “initial best conditions A1B1C2D2E2” and therefore a confirmation experiment was necessary for validation. This would be followed by measuring all responses prior calculating the GRA for the confirmation test working conditions (optimum conditions). When optimum solution was not included in the existing DOE fractional orthogonal array, equation (8) will be used to estimate value for the Grey relational grade theoretically, and subsequently an experimental value could be computed followed the confirmation test.

$$\hat{\delta} = \delta_m + \sum_{i=1}^q (\delta_i - \delta_m) \quad (8)$$

where  $\delta_m$  is the total mean of Grey relational grades (0.612),  $\delta_i$  is the mean of Grey relational grades at the optimal level and  $q$  is the number of machining parameters significantly affect Grey relational grades.

TABLE IV shows the experimental results of the confirmation trail conducted at optimum working conditions. Third column details results for process responses obtained from experimental testing using the suggested optimum conditions (confirmation test). MRR has been improved from 0.577 to 1.819 mm<sup>3</sup>/min, Ra improved from 2.711 to 2.32 μm, while ROC marginally declined from 0.053 to 0.061 mm. There was also an improvement in Grey relational grade (increased by 0.064), which was in line with the improvement in MRR and Ra results.

**TABLE IV RESULTS OF THE CONFIRMATION TEST**

|                            | Initial best conditions (Test 2)   | Optimum conditions (from the main effects of GRA)                          | Confirmation Experiment  |
|----------------------------|--|--|--|
| Level                      | A <sub>1</sub> B <sub>1</sub> C <sub>2</sub> D <sub>2</sub> E <sub>2</sub> | A <sub>1</sub> B <sub>2</sub> C <sub>2</sub> D <sub>2</sub> E <sub>2</sub> | A <sub>1</sub> B <sub>2</sub> C <sub>2</sub> D <sub>2</sub> E <sub>2</sub> |
| MRR (mm <sup>3</sup> /min) | 0.577  | -  | 1.819  |
| Ra (μm)                    | 2.711  | -  | 2.320  |
| ROC (mm)                   | 0.053  | -  | 0.061  |
| Grey relational grade      | 0.742  | 0.748  | 0.806  |

The GRA procedure successfully introduced experimental setting that produced lower surface roughness results than all 27 tests in the original experimental plan. Additionally, the associated

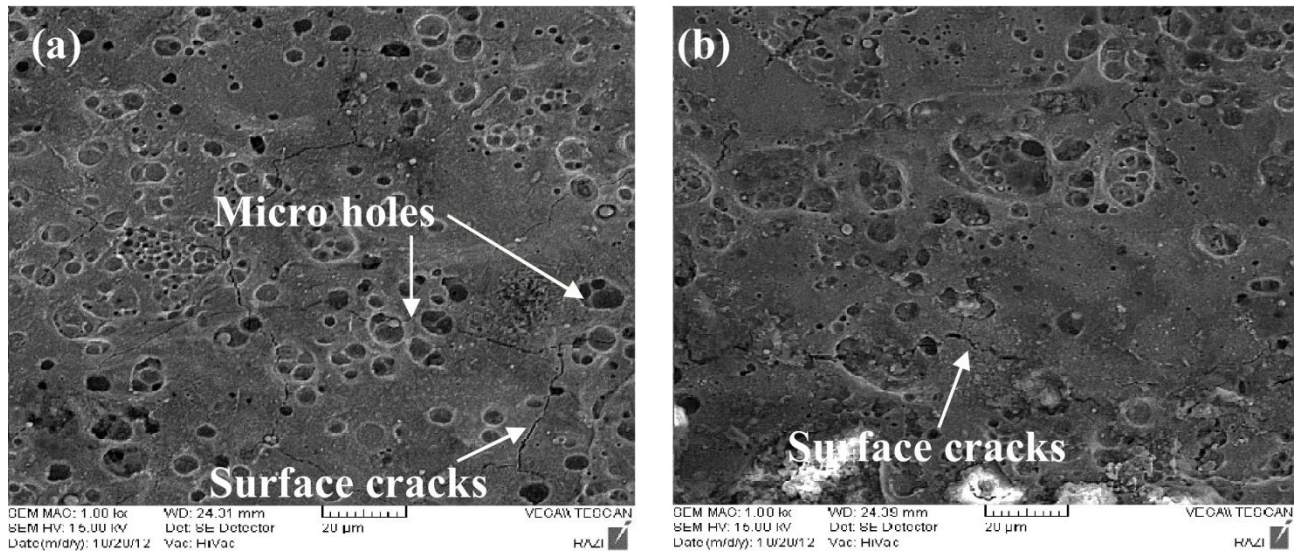


Figure 6 SEM photographs for machined surfaces of (a) initial best conditions (b) GRA optimum conditions

ROC is exceptionally close to the smallest ROC in the original plan (0.061 compared to 0.044). The only exception is the MRR results which although a significant increase was achieved compared to the initial best conditions however it is still clearly smaller than the highest MRR obtained from the original experimental plan. This could be attributed to the equal weight given to all responses and should be considered in further study.

#### D. Surface integrity of machined workpiece

SEM photographs for samples produced at initial best conditions and optimum conditions are shown in **Figure 6**. Limited variance was observed between the two cases, however, trivial change in the intensity and the size of micro holes is seen on the machined surfaces produced at initial best conditions (a) compared to those machined at optimum conditions (b). Marginally higher intensity of micro holes was observed on surfaces produced using the initial best conditions while marginally greater micro holes were obtained when the GRA optimum conditions were used. This could be attributed to the change in the pulse time (from 50 to 200  $\mu$ s). Additionally, minor surface cracks were observed in surfaces produced from both conditions.

#### V. CONCLUSION

The presented study investigates a multi-response optimisation when DEDM of steels using Grey relational analysis alongside Taguchi technique. The optimisation was performed by normalising and converting multi responses to a mono-coefficient known as Grey relational grade. The use of fractional factorial array together with grey relational analysis was employed to minimise the number of experimentation and consequently the associated cost. The following can be concluded:

- GRA was found beneficial to accurately predict the optimum/preferred working conditions when DEDM of steels.

- Optimum conditions when DEDM of steel obtained with the assistance of GRA method were  $I=15A$ ,  $T_{on}=200 \mu$ s,  $D=66$ ,  $P=2$  bar and  $N=400$  rpm (within the range of working conditions evaluated in this research).
- ANOVA results showed that  $I$  and  $P$  were statistically significant factors at the 95% confidence level.
- The optimum levels of the process control variables were subsequently used for confirmation test which introduced an improvement in the Grey relational grade from 0.742 to 0.806 with a corresponding enhancement in MRR, Ra and marginal decline in the ROC.

#### ACKNOWLEDGEMENTS

The authors would like to thank the Mechanical Engineering Department, Babol University of Technology for the technical support during the experimentation. The authors would also like to thank Department of Mechanical and Construction Engineering, Northumbria University at Newcastle for all technical advice.

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