Performance study of electrical discharge machining process in burr removal of drilled holes in Al 7075

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Abstract: Deburring is the finishing technique that is very essential for the manufacturing of precise components. Although there are various methods to remove burrs but sometimes technology requires new innovative ideas for better outcome irrespective of cost. Deburring with greater efficiency and full automation is a difficult task and this thing leads to use unconventional approaches. This research paper is all about deburring through Electric Discharge Machining process (EDM), which can be useful for finishing materials with very high precision with no men interference. For successful utilization of deburring through EDM, more intensive research including control parameters analysis of the process, is still required. In this research, the drilling operation was done on the specimen to obtain burrs and comparative study was done with different parameters and different electrodes for deburring effectively through EDM. The variable parameters were discharge current, pulse time on and pulse time off and other parameters were remained constant. Material removal rate, tool wear rate and burr height were studied as output parameters to analyse.
the performance of the combination of the input parameters for burr removal. Grey relational analysis was used to find out the optimal levels of the parameters with copper and brass electrodes respectively. It was found that copper electrode with smaller discharge current and pulse time off and larger pulse time gives better performance and brass electrode with larger discharge current and pulse time off and smaller pulse time on gives better results.

Subjects: Industrial Engineering & Manufacturing; Mechanical Engineering; Manufacturing Engineering; Production Engineering

Keywords: EDM; Al 7075; burrs; deburring; burr height; material removal rate; tool wear rate; GRA

1. Introduction

Metal is frequently machined using many processes in order to create pieces of specific shape and size. Like Drilling is a cutting process. It is the creation or enlarging of a hole in a solid material with a drill (Parker, 2003). These procedures often create ragged edges or protrusions (burrs). Removal of burrs (Deburring) is important for quality, aesthetics, functionality, and the smooth operation of working parts. It greatly improves the quality and functionality of metal and wood pieces, making it a necessary use of time and a cost effective process. A burr is a raised edge or small pieces of material remaining attached to a work piece after a modification process (https://en.wikipedia.org/wiki/Burr(edge)). It is usually an unwanted piece of material, removed with a deburring tool in a process called “deburring”. Burrs are most commonly created after machining operations, such as grinding, drilling, milling, engraving, or turning. The ISO 13715:2000 (International Standard ISO 13715:2000, 2000) defines the edge of a work piece as burred if it has an overhang greater than zero. A comprehensive definition was proposed by Beier (1999). According to it, a burr is a body created on a work piece surface during the manufacturing of a work piece, which extends over the intended and actual work piece surface and has a slight volume in comparison to the work piece, undesired, but to some extended, unavoidable (Obróbka skrawaniem, xxxx). Machining burrs typically form because of material being plastically deformed rather than cut towards the entrance or exit of a machined feature. Burrs are formed in most of the machining operations; they cannot be eliminated during the machining process, but can be minimized by controlling the process parameters, tool geometry, etc. (Jeong, HanYoo, Lee, & Min, 2009).

According to Gillespie (1999a), in drilling the burr formed at the entrance of the hole can be a result of tearing, a bending action followed by clean shearing, or lateral extrusion when chip forming and impacting of cutting edges. Kim, Min, and Dornfeld (2001) describe drilling burrs as uniform burr with or without a drill cap, crown burr, or petal burr according to their shapes and formation mechanism. When drilling stainless steel, Stein and Dornfeld (1997) revealed small or large uniform burrs as well as crown burrs, and when low alloyed steel drilling small or large uniform burrs, transient burrs and crown burrs were found. It was found that the constant ratio between burr height (BH) and undeformed chip thickness might be a fundamental property of work material for particular tool geometry (Stein & Dornfeld, 1997).

Burr shape is the most important because the burr size, and as a result, deburring cost is greatly dependent on it. Three different shapes of drilling burrs:

(A) The uniform burr has relatively small and uniform BH and thickness around the hole periphery.

(B) The crown burr has a larger and irregular height distribution around the hole.

(C) The transient burr is a type of burr formed in the transient stage between the uniform burr and the crown burr (Dornfeld, 2006).
Deburring includes both the removal of burrs and maintenance of the proper edge condition. It is usually the last process during part production, therefore the loss of potential due to any failure in deburring process is very large (Dornfield & Kim, 2001). Deburring of inaccessible, an area via conventional methods does not ensure burr removal and edge conditioning; deburring via non-conventional techniques provides a better solution (Balasubramaniam, Krishnan, & Ramakrishnan, 1998). The burr removal methods can induce dimensioning errors to the work piece if improperly executed (Dornfeld & Lisiewicz, 1992). Finally, burrs may cause problems in further processes, such as handling and assembling operations. According Aurich (2006), a study carried out in the German automotive and machine tool industries showed that the deburring causes an increase of about 15% in work force and cycle times. In addition, a 2% share in the reject rate and a 4% share in machine breakdown times due to burrs. Averaging the presented distribution without any weight factors the share accounts of up to 9% of total manufacturing cost. An economic evaluation of the impact of burrs related Aurich has provided production cost too (Aurich, 2006): the costs are estimated at up to 500 million Euro expense per year only in Germany.

There is no standard procedure to remove burrs having different shape and dimensions. For removing burrs of different sizes and shapes. There are many ways of deburring to remove the burr, they are conventional deburring process namely manual deburring, hand deburring etc. and non-conventional deburring process (Prathap, Raghavendra, & Shetty, 2012). Conventional deburring processes necessitate time, labour and other associated costs. Manual deburring results in inconsistent quality. Repeatability is hard to achieve as it is done manually (Gillespie, 1999b). The limitations of traditional finishing led to the development of advanced finishing techniques like Abrasive Flow Machining, Magnetic Abrasive Finishing, and Ion Beam Machining, Electric Discharge Machining. Deburring through Electric Discharge Machining process (EDM) is one of the best options when better outcome is expected (in comparison to conventional methods) and overall cost of the process is not a constraint.

1.1. Electric discharge machining
It is a manufacturing process whereby a desired shape is obtained using electrical discharges (sparks). Material is removed from the work piece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric liquid and subject to an electric voltage. One of the electrodes is called the tool-electrode, or simply the “tool” or “electrode”, while the other is called the work piece-electrode, or “work piece”. In this process, the metal is removed from the work piece due to erosion case by rapidly recurring spark discharge taking place between the tool and work-piece. The electrode and the work piece must have electrical conductivity in order to generate the spark (Abbas, Solomon, & Bahari, 2006). EDM is a non-conventional machining process but the technique of material erosion employed in EDM is still debatable (Tsai & Wang, 2001). The basic principal followed is the conversion of electrical energy into thermal energy through a series of discrete electrical discharges occurring between the electrode (tool) and work piece immersed in a dielectric fluid (Kalpajan & Schmid, 2003). Due to the insulating effect of the dielectric, which is used in EDM, process is very important because it avoids electrolysis of the electrodes during the EDM process. Spark is initiated when high voltage is applied between the electrode and work piece at smallest point distance. Metal starts eroding from both the surfaces of work piece as well as electrode. At the end, sparks spread over the entire work piece surface and it leads to the erosion, or machining to a shape, which is mirror image of the tool.

| Input process parameters of EDM | Output parameters or responses |
|---------------------------------|--------------------------------|
| Discharge current               | Material removal rate          |
| Pulse time on                   | Tool wear rate                 |
| Pulse time off                  | Burr height                    |

Surendra and Dabade (2011) investigated that the quality of the burr removed with brass electrode is better as compared with aluminium and copper electrodes. Secondly, it observed that the
Aluminium electrodes wear is more irrespective of process parameters due to lower electrical conductivity than other electrodes. Finally, it is concluded that the brass electrodes gives better results in terms of quality, material removal rate (MRR), and electrode wear than aluminium and copper electrodes. Again Dabade (2013) investigated the effect of different EDM process parameters such as current, dielectric flow rate and pulse on time on the tool wear rate (TWR) and grading of deburred holes by visual inspection for burr removal in drilled holes of Inconel-718 material. Burr removal operation were carried out with two types of electrode materials such as Aluminum and Brass with cylindrical taper geometry at tip is used. John and Davis (2015, 2016) did the drilling operation on the OHNS specimen material and obtained burrs and comparative study was done with different parameters and different electrodes (copper and brass) for deburring effectively through EDM. Optimal levels of the parameters for deburring on OHNS with copper electrodes and brass electrodes were obtained respectively. Again John et al. (2015) investigated the burr removal through EDM process on D2 steel with copper and brass electrodes and optimized combination of process parameters were obtained for MRR, TWR and BH removal.

It is important to select machining parameters for achieving optimal machining performance (Tarng, Ma, & Chung, 1995). Usually, the desired machining parameters are determined based on experience or on handbook values. However, this does not ensure that the selected machining parameters result in optimal or near optimal machining performance for that particular electrical discharge machine and environment. So research is needed in this area to find out the optimal parameters for the deburring operation through EDM for various widely used specimen materials like titanium, aluminium alloys, steels, advanced materials etc.

1.2. Optimization technique
It is a mathematical results and numerical methods for finding and identifying the best candidate from a collection of alternatives without having to explicitly enumerate and evaluate all possible alternatives. The process of optimization lies at the root of engineering, since the classical function of the engineering is to design new, better, more efficient and less expensive systems as well as to devise plans and procedures for the improved operation of existing systems.

2. Details of the experiment
To obtain the burrs and to see the burr formation, each work piece was drilled by HSS cutting tool in the wet cutting conditions. Further, EDM operations were performed to measure MRR and TWR on each work piece. In order to study the effect of three different parameters (current supply, pulse time on, and pulse time off with different electrodes) on the burr removal of the specimens.

2.1. Details of the specimen materials selected for the proposed research work
Aluminium 7075 (Figure 1) were chosen to be the specimen materials. The material composition of specimen material Al 7075 is shown in Table 1 and mechanical properties are shown in Table 2 respectively. Al 7075 is often used in transport applications, including marine, automotive and aviation, due to their high strength-to-density ratio. Its strength and lightweight is also desirable in other fields. Rock climbing equipment, bicycle components, inline skating-frames, and hang glider air-frames are commonly made from 7075 aluminium alloy. Hobby grade RC models commonly use 7075 and 6061 for chassis plates. One interesting use for 7075 is in the manufacture of M16 rifles for the American military. In particular high quality M16 rifle lower and upper receivers as well as extension tubes are typically made from 7075-T6 alloy. Desert Tactical Arms and French armament
company PGM use it for their precision rifles. It is also commonly used in shafts for lacrosse sticks, such as the STX sabre, and camping knife and fork sets. Due to its high strength, low density, thermal properties, and its ability to be highly polished, 7075 is widely used in mold tool manufacture (http://www.azom.com/article.aspx?ArticleID=6652).

2.2. Cutting tools used

2.2.1. Brass
Brass is the generic term for a range of copper-zinc alloys with differing combinations of properties, including strength, machinability, ductility, wear-resistance, hardness, colour, antimicrobial, electrical, and thermal conductivity, corrosion resistance. Brass has higher malleability than bronze or zinc. The relatively low melting point of brass (900 to 940°C, 1,652 to 1,724°F, depending on composition) and its flow characteristics make it a relatively easy material to cast (Walker, xxxx).

2.2.2. Copper
Copper has properties, such as its high electrical conductivity, tensile strength, ductility, creep (deformation) resistance, corrosion resistance, low thermal expansion, high thermal conductivity, solder ability, and ease of installation. Copper is a chemical element with symbol Cu and atomic number 29. It is a ductile metal with very high thermal and electrical conductivity. Pure copper is soft and malleable. A freshly exposed surface has a reddish-orange colour (http://www.gsa.org.au/resources/factites/factitesCopper.pdf).
2.3. Grey relational analysis

Deng proposed it in 1989 as cited in is widely used for measuring the degree of relationship between sequences by grey relational grade. Several researchers to Optimize control parameters having multi-responses through grey relational grade apply grey relational analysis. Deng (1989) had proposed Grey relational analysis in the Grey theory that was already proved to be a simple and accurate method for multiple attributes decision problems (Chang, 1996; Hsu, 1997; Luo & Kuhnell, 1993; Tzeng & Tsaur, 1994), especially for those problems with very unique characteristic (Chiang, 1997; Wu, 1998). This analytical model magnifies and clarifies the Grey relation among all factors. It also provides data to support quantification and comparison analysis (Sih, 1997). In other words, the Grey relational analysis is a method to analyze the relational grade for discrete sequences. This is unlike the traditional statistics analysis handling the relation between variables. The use of grey relational analysis to optimize the burr removal operations includes the following steps:

(A) Design of experiment:
- To identify the performance characteristics and machining parameters to be evaluated.
- To determine the number of levels for the process parameters.
- To select the appropriate orthogonal array and assign the machining parameters to the orthogonal array.

(B) Perform experiments (collecting experimental data).

(C) Grey relational analysis:
- To perform the grey relational generating (data pre-processing and deviation sequences) and calculate the grey relational coefficient.
- To calculate the grey relational grade by averaging the grey relational coefficient.
- To analyses the experimental results using the grey Relational grade.
- To select the optimal levels of machining parameters.

In the grey relational analysis method, experimental data (electrode wear ratio, material wear rate, surface roughness) are first normalized in the range between zero and one, which is also called the grey relational generation. Next, the grey relational coefficient is calculated from the normalized experimental data to express the relationship between the desired and actual experimental data. Then, the grey relational grade is computed by averaging the grey relational coefficient corresponding to each process response. The overall evaluation of the multiple process responses is based on the grey relational grade. As a result, optimization of complicated multiple process responses can be converted into optimization of a single grey relational grade. In other words, the grey relational grade can be treated as the overall evaluation of experimental data for the multi-response process.
The optimal level of the process parameters is the level with the highest grey relational grade. In Figure 2 these steps are shown in flow chart to easily understand the various steps of GRA.

### 2.3.1. Data pre-processing

In grey relational analysis, the data pre-processing is the first step performed to normalize the random grey data with different measurement units to transform them to dimensionless parameters. Thus, data pre-processing converts the original sequences to a set of comparable sequences. Different methods are employed to pre-process grey data depending upon the quality characteristics of the original data. The original reference sequence and pre-processed data (comparability sequence) are represented by

\[ X_0^{(i)}, \quad X_i^{(k)}, \quad i = 1, 2, \ldots, m; \quad k = 1, 2, \ldots, n \]

where \( m \) is the number of experiments and \( n \) is the total number of observations of data. Here, \( X_i \) represents the \( i \)th experimental results and is called the comparative sequence in grey relational analysis. \( X_0^{(k)} \) and \( X_i^{(k)} \) represent the numeric value of \( k \)th element in the reference sequence and the comparative sequence, respectively.

Depending upon the quality characteristics, the three main categories for normalizing the original sequence:

- If the original sequence data has quality characteristic as “larger-the-better” then the original data is pre-processed as “larger-the-best”

\[
X_i^{(k)} = \frac{X_0^{(k)} - \min X_i^{(0)}(k)}{\max X_i^{(0)}(k) - \min X_i^{(0)}(k)}
\]  

(1)

- If the original data has the quality characteristic as “smaller-the-better”, then original data is pre-processed as “smaller-the-best”

\[
X_i^{*}(k) = \frac{\max X_i^{(0)}(k) - X_i^{(0)}(k)}{\max X_i^{(0)}(k) - \min X_i^{(0)}(k)}
\]  

(2)

However, if the original data has a target optimum value (OV) then quality characteristic is “nominal-the-better” and the original data is pre-processed as “nominal-the-better”

\[
X_i^{*}(k) = 1 - \frac{|X_i^{(0)}(k) - OV|}{\max \{\max X_i^{(0)}(k) - OV, OV - \min X_i^{(0)}(k)\}}
\]  

(3)

In addition, the original sequence is normalized by a simple method in which all the values of the sequence are divided by the first value of the sequence.

\[
X_i^{*}(k) = \frac{X_i^{(0)}(k)}{X_i^{(0)}(1)}
\]  

(4)

where \( \max X_i^{(0)}(k) \) and \( \min X_i^{(0)}(k) \) are the maximum and minimum values respectively of the original sequence \( X_i^{(0)}(k) \). Comparable sequence \( X_i^{*}(k) \) is the normalized sequence of original data of the \( k \)th element in the \( i \)th sequence.

### 2.3.2. Grey relation grade

Next step is the calculation of deviation sequence, \( \Delta O_i(k) \) from the reference sequence of pre-processed data \( X_i^{*}(k) \) and the comparability sequence \( X_i^{*}(k) \). The grey relational coefficient is calculated from the deviation sequence using the following relation:
where $\Delta O_i(k)$ is the deviation sequence of the reference sequence $X_0^*(k)$ and comparability sequence $X_i^*(k)$.

\[
\Delta O_i(k) = |X_0^*(k) - X_i^*(k)|
\]  

(6)

$\Delta \max = \max_{ij,k} |X_0^*(k) - X_i^*(k)|$  

(7)

$\Delta \min = \min_{ij,k} |X_0^*(k) - X_i^*(k)|$  

(8)

$\xi$ is the distinguishing coefficient $\xi \in [0,1]$. The distinguishing coefficient ($\xi$) value is chosen to be 0.5. A grey relational grade is the weighted average of the grey relational coefficient and is defined as follows:

\[
\gamma(X_0^*(k), X_i^*(k)) = \frac{\Delta \min + \xi \Delta \max}{\Delta O_i(k) + \xi \Delta \max} \quad 0 < \gamma(X_0^*(k), X_i^*(k)) \leq 1
\]  

(5)

The grey relational grade ($X_0^*, X_i^*$) represents the degree of correlation between the reference and comparability sequences. If two sequences are identical, then grey relational grade value equals unity. The grey relational grade implies that the degree of influence related between the comparability sequence and the reference sequence. In case, if a particular comparability sequence has more influence on the reference sequence than the other ones, the grey relational grade for comparability and reference sequence will exceed that for the other grey relational grades. Hence, grey relational grade is an accurate measurement of the absolute difference in data between sequences and can be applied to appropriate the correlation between sequences.

A higher value of the grey relational grade represents a stronger relational degree between the reference sequence $X_0(k)$ and the given sequence $X_k(k)$. A higher value of the grey relational grade means that the corresponding process parameter is closer to the optimal one. In other words, optimization of the complicated multiple process responses can be converted into optimization of a single grey relational grade.

3. Methodology

For the proposed work, the following methodology was adopted:

(I) To prepare the specimen.

(II) To prepare the electrode tools.

(III) To perform drilling operation on the specimen.

(IV) To investigate the following:
   - Burrs height measurement.
   - Weight measurement.

(V) To perform EDM operation to remove burrs with define parameters.

(VI) To investigate the following after EDM process:
   - Burrs height measurement.
   - Weight measurement.

(VII) To analyse tool electrode weight.

(VIII) To find optimal results through Grey relational analysis based calculation.
Al 7075 was cut in desired dimensions by handsaw. The dimensions are shown in Table 3. The brass and copper electrode rods also were cut into small pieces as per required dimensions shown in Table 4. Then drilling operations were performed on each work piece to obtain burrs. Two holes were drilled on each work piece and BH were measured with digital Vernier callipers. Variety of burrs were formed as shown in Figures 3–5. Then average BHs, weight of the specimen were calculated for calculation purpose. Later EDM machining were done on each work piece according to L4 array as shown in Table 5 with three factors and two levels as shown in Table 6. The experimental setup of EDM machine is shown in Figure 6.

### Table 3. Dimensions of specimen

| Specimen material Al 7075 |   |   |
|--------------------------|---|---|
| Length                   | 40 ± 0.5 |
| Breath                   | 30 ± 0.5 |
| Height                   | 25 ± 0.5 |

### Table 4. Dimensions of electrodes

|          | Brass | Copper |
|----------|-------|--------|
| Diameter | 5 ± 0.5 | 5 ± 0.5 |
| Length   | 30 ± 0.5 | 30 ± 0.5 |

### Table 5. Standard L4 orthogonal array

| Experiment no. | Factor A | Factor B | Factor C |
|----------------|----------|----------|----------|
| 1              | 1        | 1        | 1        |
| 2              | 1        | 2        | 2        |
| 3              | 2        | 1        | 2        |
| 4              | 2        | 2        | 1        |
4. Results and discussion

The factors were varied at two levels for burr removal machining operations in EDM process. Analysis of the results was carried out analytically as well as graphically. All the statistical calculations and plots were generated by MINITAB17 software.

These were four optimal combinations of the parameters at which experimental processes were performed and the corresponding MRR, TWR and BH were found out by the following formulas:

\[
MRR = \left( \frac{E_2 - E_1}{\rho \times t} \right) \times 1000 \text{ mm}^3/\text{s} \quad (10)
\]

where \( E_1 \) = weight of material before EDM in gm; \( E_2 \) = weight of material after EDM in gm; \( \rho \) = density of the material in gm/cm\(^3\); \( T \) = machining time in seconds.

\[
TWR = \left( \frac{E_2 - E_1}{\rho \times t} \right) \times 1000 \text{ mm}^3/\text{s} \quad (11)
\]

where \( E_1 \) = weight of material before EDM in gm; \( E_2 \) = weight of material after EDM in gm; \( \rho \) = density of the material in gm/cm\(^3\); \( T \) = machining time in seconds.

\[
BH = (Y_2 - Y_1) \text{ mm} \quad (12)
\]

where \( Y_1 \) = burr height before EDM machining; \( Y_2 \) = burr height after EDM machining.

4.1. With copper electrode

Table 7 presents the experimental result and effect of three input control parameters (discharge current, pulse time on and pulse time off) on Al 7075 with copper electrode in terms of three output parameters (material removal rate, TWR and burr height). It is observed by the Table 7 that Copper Electrode gives High MRR and Low TWR in comparison of brass electrode.
Table 8 represent data pre-processing results for EDM operation on specimen with copper electrode. For MRR “largest is best” (Equation (1)) and for TWR and BH “smallest is best” (Equation (2)) is used. Here in this case \( k = 1, 2, 3 \) and \( i = 1, 2, 3, 4 \).

Table 9 represents the Deviation Sequence for EDM Operation for out parameters. The deviation sequences \( \Delta O_i(k) \), \( \Delta O_{i\text{max}}(k) \) and \( \Delta O_{i\text{min}}(k) \) were calculated. The deviation sequences \( \Delta O_1(k) \) were calculated as: \( \Delta O_i(k)=|x_0(k) - x_i(k)| = |1.0000 - 0.000| = 1.0000 \).

In Table 10 grey relational grades are shown, the Grey relational grades show the level of correlation between the reference and the comparability sequences, the larger Grey relational grade means the comparability sequence exhibiting a stronger correlation with the reference sequence. So here, combination 1, 2 and 4 tells the optimal combination of parameters.

The response table was used to calculate the average Grey relational grades for each factor level, as listed in Table 11. Based on this study, a combination of the levels that provide the largest average response can be selected. Here from Table 11 the optimal levels \( A_1, B_2, \) and \( C_1 \) were found.

From MINITAB 17 software graphs were obtained for each output, parameters (Figures 7–9). Contour graphs are surface graphs plotted in 2D space. Viewing a contour graph is the same as viewing a 3D surface graph from a vantage point perpendicular to the XZ plane. In contour graphs, different colours or levels of gray scale, labelled contour lines, or both distinguish ranges of Z values.

Figure 7(A) and (B) depicts that maximum MRR was found when the discharge current values were kept between 6 and 7 Amp. and pulse time on values between 10.6 and 10.8 \( \mu \)s with all the chosen level of pulse time off. Similarly, Figure 8(A) and (B) depicts that minimum TWR was found when the discharge current values were kept between 7 and 8 Amp and pulse time on values between 10.4 and 10.6 \( \mu \)s with all the chosen level of pulse time off. Figure 9(A) and (B) depicts that maximum burr height removal (BH) was found when the discharge current values were kept between 7 and 8 Amp and pulse time on values between 10.4 and 10.6 \( \mu \)s with all the chosen level of pulse time off.
4.2. With brass electrode

With brass electrode, all calculations were done as it was done with copper electrode. Here, Table 12 presents the experimental result and effect of three input control parameters on Al 7075 with brass electrode in terms of output parameters. It was investigated by Table 12 that brass electrode gives Low MRR and High TWR in compare of Copper Electrode.

Table 13 represent data pre-processing results for EDM operation on specimen with copper electrode.

Table 9. Deviation sequence for EDM operation on “Al 7075” with copper electrode

| Run no. | Material removal rate (mm³/s) | Tool wear rate (mm³/s) | Burr height (mm) |
|---------|------------------------------|------------------------|-----------------|
| 1       | 0.00                         | 0.00                   | 1.00            |
| 2       | 0.50                         | 0.00                   | 0.10            |
| 3       | 1.00                         | 1.00                   | 0.03            |
| 4       | 1.00                         | 0.00                   | 0.00            |

Table 10. Calculated grey relational coefficients and grey relational grade for EDM operation on “Al 7075” with copper electrode

| Experiment no. | Grey relational coefficient for MRR | Grey relational coefficient for TWR | Grey relational coefficient for BH | Grey relational grade |
|----------------|-------------------------------------|-----------------------------------|-----------------------------------|-----------------------|
| 1              | 1.00                                | 1.00                              | 0.3333                            | 0.7778                |
| 2              | 0.50                                | 1.00                              | 0.8333                            | 0.7778                |
| 3              | 0.33                                | 0.33                              | 0.9433                            | 0.5366                |
| 4              | 0.33                                | 1.00                              | 1.0000                            | 0.7778                |

Table 11. Response table for grey relational grade for EDM operation on “Al 7075” with copper electrode

| Levels | Factors |
|--------|---------|
| A      | B       | C       |
| 1      | 0.7778  | 0.6572  | 0.7778 |
| 2      | 0.6572  | 0.7778  | 0.6572 |

Figure 7. (A) Contour plot for Al 7075 specimen showing the effect on MRR with respect to Pulse time off and Discharge Current when machined with Copper electrode; (B) Contour plot for Al 7075 specimen showing the effect on MRR with respect to pulse time off and pulse time on when machined with copper electrode.

Table 13 represent data pre-processing results for EDM operation on specimen with copper electrode.
Figure 8. (A) Contour plot for Al 7075 specimen showing the effect on TWR with respect to pulse time off and discharge current when machined with copper electrode; (B) Contour plot for Al 7075 specimen showing the effect on TWR with respect to pulse time off and pulse time on when machined with copper electrode.

Figure 9. (A) Contour plot for Al 7075 specimen showing the effect on BH with respect to pulse time off and discharge current when machined with copper electrode; (B) Contour plot for Al 7075 specimen showing the effect on BH with respect of pulse time off and pulse time on when machined with copper electrode.

Table 12. Results of experimental trial runs for EDM on “Al 7075” with brass electrode

| Experiment no. | Discharge current (Amp) | Pulse time on (μs) | Pulse time off (μs) | Material removal rate (mm³/s) | Tool wear rate (mm³/s) | Burr height (mm) |
|----------------|------------------------|--------------------|---------------------|-------------------------------|------------------------|-----------------|
| 1              | 5                      | 10                 | 6                   | 1.190476190                   | 0.389863548            | 0.125           |
| 2              | 5                      | 11                 | 7                   | 0.238095238                   | 0.389863548            | 0.065           |
| 3              | 10                     | 10                 | 7                   | 0.714285714                   | 0.077972710            | 0.035           |
| 4              | 10                     | 11                 | 6                   | 1.190476190                   | 0.467836257            | 0.01            |
| Average        |                        |                    |                     | 0.833333333                   | 0.331384016            |                 |
Table 13. Data pre-processing result for EDM operation on “Al 7075” with brass electrode

| Run no. | Material removal rate (mm^3/sec) | Tool wear rate (mm^3/s) | Burr height (mm) |
|---------|----------------------------------|-------------------------|-----------------|
| 1       | 1.00                             | 0.1998                  | 0.0             |
| 2       | 0.00                             | 0.1998                  | 0.52            |
| 3       | 0.50                             | 1.0000                  | 0.78            |
| 4       | 1.00                             | 0.0000                  | 1.0             |
Table 14 represents the deviation sequence for EDM operation for out parameters.

Here in Table 15, by the grey relational grade the optimal combination of machining was found No. 4.

The response table was used to calculate the average Grey relational grades for each factor level, as listed in Table 16. Based on this study, a combination of the levels that provide the largest average response can be selected. Here from response Table 16 the optimal levels A₂, B₁, and C₁ were found.

From MINITAB17 software graphs were obtained for each output, parameters (Figures 10–12). Here also in contour plot shows the effect on output parameters with different level of input parameters. Figure 10(A) and (B) depicts that maximum MRR was found when the discharge current values

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**Table 14. Deviation sequence for EDM operation on “Al 7075” with brass electrode**

| Run no. | Material removal rate (mm³/s) | Tool wear rate (mm³/s) | Burr height (mm) |
|---------|-------------------------------|------------------------|------------------|
| 1       | 0.00                          | 0.8002                 | 1.0              |
| 2       | 1.00                          | 0.8002                 | 0.48             |
| 3       | 0.50                          | 0.0000                 | 0.22             |
| 4       | 0.00                          | 1.0000                 | 0.00             |

**Table 15. Calculated grey relational coefficients and grey relational grade for EDM operation on “Al 7075” with brass electrode**

| Experiment no. | Grey relational coefficient for MRR | Grey relational coefficient for TWR | Grey relational coefficient for BH | Grey relational grade |
|----------------|-------------------------------------|------------------------------------|----------------------------------|-----------------------|
| 1              | 1.00                                | 0.3845                             | 0.3333                           | 0.5726                |
| 2              | 0.33                                | 0.3845                             | 0.5102                           | 0.4082                |
| 3              | 0.50                                | 1.0000                             | 0.6944                           | 0.7315                |
| 4              | 1.00                                | 0.3333                             | 1.0000                           | 0.7778                |
were kept between 7 and 8 Amp and pulse time on values between 10.4 and 10.6 μs with all the chosen level of pulse time off. Similarly, Figure 11(A) and (B) depicts that minimum (TWR) was found when the discharge current values were kept between 6 and 7 Amp and pulse time on values between 10.2 and 10.4 μs with all the chosen level of pulse time off. Figure 12(A) and (B) depicts that maximum burr height removal (BH) was found when the discharge current values were kept between 6 and 7 Amp. And pulse time on values between 10.4 and 10.6 μs with all the chosen level of pulse time off.

The outcomes of the research are shown in Figures 13(A) and (B) and 14(A) and (B).

5. Conclusion

In the present research work, drilling operations were performed on specimen material Al 7075 to investigate the formation of burr and their removal to the maximum extent as per the recommendations of latest research works. The research work consisted of removal of burrs (deburring) though EDM unconventional machining method. Optimum combinations were obtained for machining parameters such as discharge current, pulse time on and pulse time off for BH, TWR, MRR through Grey Relational Analysis.

Following were the conclusions:

- Copper Electrode gives high MRR in compare of Brass Electrode while machining Al 7075.
- Brass Electrode gives high TWR in compare of Copper Electrode while machining Al 7075.

| Levels | Factors |
|--------|---------|
|        | A       | B       | C       |
| 1      | 0.4904  | 0.6520  | 0.6752  |
| 2      | 0.7546  | 0.5930  | 0.5698  |
• In deburring of Al 7075, Copper electrode should be used with smaller discharge current and pulse time off and larger pulse time to obtain better performance.

• In deburring of Al 7075, Brass electrode should be used with larger discharge current and pulse time off and smaller pulse time on to obtain better performance.

• Various contour plots indicated the effect of the input control process parameters on material removal rate and TWR and differences in burr heights.

Deburring is directly connected to MRR. The use of electrode depends on the input process parameters, like while using high discharge current Brass electrode should be preferred and when pulse time on is high Copper electrode gives better performance and similarly for high pulse time off Brass electrode is good. In this case Copper electrode gives high MRR and low TWR which is desirable.

6. Future work

(a) For successful utilization of EDM deburring, more intensive research including parameters analysis of the process is still required.

(b) Research can be carried out with various electrodes materials.

(c) In this research for every specimen new electrode were used to avoid non-uniform tool edge problem but in the days to come research can be done on the tool geometry also.

(d) Research can be carried out with hollow cylindrical electrode also.

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