Characterization of electric discharge machining of titanium alloy utilizing MEIOT technique for orthopedic implants

Manoj Prabhakar B S, Ranjith R① and Venkatesan S②③
1 Assistant Professor, Department of Mechanical Engineering, CSI College of Engineering, Ketti, Nilgiris, TamilNadu, India
2 Assistant Professor, Department of Mechanical Engineering, SNS College of Technology, Coimbatore, TamilNadu, India
3 Lecturer, School of Mechanical Engineering, College of engineering and technology, Wachemo University, Hosaena, Ethiopia
E-mail: ranjith.mecs@gmail.com

Keywords: composite tools, hybrid optimization, orthopedic application, electric discharge machining, surface morphology

Abstract
In this research work, medical grade titanium alloy Ti4Al6V was electric discharge machined with an objective of attaining mirror finish for orthopedic implants. Experiments were conducted by varying tool materials, discharge current, pulse on time and pulse off time whereas the responses chronicled are material removal rate, electrode wear rate and surface roughness. The aluminium (A), copper (C) and aluminium alloy reinforced with graphite particles of various weight percentage (5-A1,10-A2,15-A3) were used as tool materials. The composites were fabricated using stir casting technique. The findings showed that the titanium alloy machined with A1 composite tool offers the highest MRR, the C tool has the lowest EWR, and the A2 composite tool results in good surface finish. The surface of specimens produced using A1 tool exhibits poor surface quality owing to the eczema surface. Specimens machined with the C tool have a remelted layer, pockmarks, and an uneven fusion structure, which were not present in specimens machined with the A2 tool. MOORA-ELECTRE Integrated Optimization Technique (MEIOT) was applied to select the best parametric combination and the best electrode material.

1. Introduction
The materials predominantly used as medical implants are nitinol, stainless steel, and cobalt-chromium alloys. The strength, elasticity and stiffness are the basic properties for materials in human implants [1–3]. Because of its harmonizing factor, Ti4Al6V, a medical grade titanium alloy, was recommended as orthopedic implants [4]. The substrate scuff caused by conventional processes results in certain electrochemical responses [5]. In general, the lot of literature incorporates research on mechanization and surface experiments for industrial titanium-based alloys using conventional machining methods [6–8].

Suitable methods of machining must be selected to produce implants of good surface [9]. The Electric Discharge Machining (EDM) was suitable to manufacture medical implants with a high degree of accuracy [10, 11]. The major process parameters influencing machining efficiency are current, pulse on time, pulse off time, voltage, gap width and dielectric medium [12–15]. From the literature survey, it was revealed that current and pulse on time are the most dominant factors influences the characteristic of the machining [16, 17].

Selecting suitable combination of electrode materials and workpiece yields better results. Fly ash reinforced AA6061 composite was EDM ed utilizing copper and brass electrodes. When brass was used as an electrode, maximum MRR was achieved, and less EWR was registered for copper electrode [18]. In case of SiC reinforced AA6061 composites copper and brass electrode showed better MRR and R, value respectively [19]. The same results were obtained when machining the Nimonic 75 alloy [20]. The graphite, tungsten, brass and copper tool were used for the machining of INCONEL 825 super alloy. As opposed to unflushed machining, flushing of machined debris improved MRR. The findings showed that thermal conductivity of the electrode influences the MRR and R, [21].
AISI D2 tool steel were machined by varying discharge current, gap voltage, pulse on time and tool materials. Material Removal Rate (MRR) and Electrode Wear Rate (EWR) were recorded as response. It has been claimed that machined with brass metal yields better results than copper tools [22]. Ramesh et al performed Powder mixed EDM of AISI P20 steel by varying tool materials. It was concluded that copper tool and tungsten tool machined under Aluminium Oxide (Al₂O₃) mixed dielectric medium offers better MRR and least EWR respectively [23]. Titanium grades 6 alloy was machined with electrodes of copper, brass, and zinc. Brass offers higher MRR, whereas copper bestows lower EWR and a better surface quality [24]. Copper tools are best suited for finishing operations, while aluminium electrode was ideal for roughing operations [25] and owing to its higher melting temperature Copper-tungsten tool offer least EWR [26]. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [27], Multi-Objective Optimization method by Ratio Analysis (MOORA) [28], Elimination Et Choix Traduisant la REalité (ELECTRE) [29], Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) [30], Grey Relational Approach (GRA) [31] and Weighted Aggregates Sum Product Assessment (WASPAS) [32] are the various optimization technique used by researchers to find the best from the available alternatives. Numerous researchers successfully applied MOORA technique for parametric optimization and reported that it is an efficient and time-saving technique [33–35]. ELECTRE was created on the base of distance measurement among two particles. This method was applied to find out the best attribute [36–38].

Researchers do a lot of work by varying the tool materials, but only a few studies have been published on machining using composite tools. In this work, an attempt was made to machine the Ti6Al4V titanium alloy using an AA6061 / Graphite composite tool with the objective of attaining a mirror finish. Experiments were carried out by changing the electrode materials, discharge current, pulse off time, and pulse on time, whereas MRR, EWR, and Ra were recorded as responses. The surface morphology was analyzed with the aid of Scanning Electron Microscope. MOORE-ELECTRE optimization technique was Integrated and used to find out the optimal parametric combination as well as best electrode materials.

2. Materials and methods

About 1kg of AA6061 was kept in a graphite crucible and its chemical composition was depicted in the table 1. The crucible was heated to the temperature of 700 °C and preheated graphite (Gr) particles of average particle size 5 μm was added to the charge. The mixture was stirred for 180 s using a mechanical stirrer at a speed of 1000 RPM. An equal weight proportion of Potassium Titanium Fluoride (K₂TIF₆) was added as a flux to improve the wettabiliy of reinforcing particles. The mixture was stirred for 120 s after the flux was added. The charge was then poured into the preheated mould made of die steel. The same procedure was followed for the manufacturing of composites with different weight percentage. The AA6061 / 5%Gr (A1), AA6061 / 10%Gr (A2), AA6061 / 15%Gr (A3), Aluminium (A) and Copper (C) was used as an electrode material. The EDM experiments were carried out on medical graded titanium alloy (Ti6Al4V) by varying electrode materials, Pulse on time, Pulse off time and discharge current. The selected parameters were varied at 5 level as shown in table 2 and experimental runs were designed using L25 Taguchi orthogonal design. The MRR and EWR were determined by measuring the ratio of weight difference before and after machining to the product of machining time and density, as shown in equations (1) and (2). The specimens were machined for the time span of 10 min. The surface roughness was measured using the SJ210 testing machine manufactured by Mitutoyo. The value was

| Table 1. Chemical composition of AA6061 Aluminium Alloy. |
|----------------------------------|
| Element | Si | Cu | Mg | Cr | Al |
| % Composition | 0.59 | 0.29 | 1.1 | 0.2 | 97.8 |

| Table 2. Process parameters and its levels. |
|----------------------------------|
| Process parameters | Copper, AA6061, AA6061/3Gr, AA6061/10Gr, AA6061/15Gr |
| Levels | 15, 30, 45, 60, 75 |
| Current (A) | 07, 14, 21, 28, 35 |
| Pulse OFF Time (μs) | 2, 4, 6, 8, 10 |
| Dielectric fluid | EDM Oil |

MRR, EWR, and Ra were recorded as responses. The surface morphology was analyzed with the aid of Scanning Electron Microscope. MOORE-ELECTRE optimization technique was Integrated and used to find out the optimal parametric combination as well as best electrode materials.
measured on ten different points on the specimen surface and average was recorded as surface roughness. Scanning Electron microscope was used to examine the surface morphology.

\[ \text{MRR} = \frac{(W_b - W_d)}{\rho \times t} \]  
\[ \text{EWR} = \frac{(L_b - L_d)}{\rho \times t} \]

3. MOORA-electre integrated optimization technique (MEIOT)

The MEIOT method was used to determine the right parametric combination and best electrode material. The efficiency of the alternatives was compared to each other and the one with the most exaggerated performance was chosen as the best. The available alternatives for assessment in this dilemma are A, A, A1, A2, and A3. The procedure began with the formulation of a decision matrix, since the engineering problem had 25 experimental runs, which were denoted in the I element, and it was analysed with the aid of three responses, namely MRR, EWR and Ra, which were denoted in the j element, resulting in a decision matrix of \( \times 3 \) as shown in table 3.

Following that the matrix was normalised utilizing the equation (3)\(^{[39]} \).

\[ A_{ij} = \left( \frac{X_{ij}^2}{\sum_{i=0}^{n} X_{ij}^2} \right) \]

\[ A_{11} = \left( \frac{0.16^2}{\sum_{i=0}^{16.33} 0.15678} \right) \]

Correlation between these normalised value and standard deviation of the experimental response was determined as per the equation (4). A matrix was generated by multiplying the correlation and standard

### Table 3. Formation of decision matrix from experimental results.

| S.No | Electrode material | Pulse on time (\( \mu s \)) | Pulse off time (\( \mu s \)) | IP current (A) | MRR (mm\(^3\) min\(^{-1}\)) | EWR (mm\(^3\) min\(^{-1}\)) | Surface roughness (\( \mu m \)) |
|------|-------------------|-----------------|-----------------|-------------|-----------------|-----------------|-----------------|
| 1    | A1                | 45              | 6               | 7           | 0.16            | 0.0011          | 1.37            |
| 2    | A1                | 15              | 4               | 14          | 0.6             | 0.0015          | 3.571           |
| 3    | A1                | 60              | 2               | 21          | 0.5             | 0.0027          | 7.51            |
| 4    | A1                | 30              | 10              | 28          | 0.375           | 0.0036          | 3.224           |
| 5    | A1                | 75              | 8               | 35          | 0.45            | 0.0052          | 6.653           |
| 6    | A2                | 60              | 8               | 7           | 0.1             | 0.0016          | 0.847           |
| 7    | A2                | 30              | 6               | 14          | 0.145           | 0.0015          | 3.89            |
| 8    | A2                | 75              | 4               | 21          | 0.4             | 0.0029          | 7.918           |
| 9    | A2                | 45              | 2               | 28          | 0.485           | 0.0033          | 8.603           |
| 10   | A2                | 15              | 10              | 35          | 0.305           | 0.0051          | 6.933           |
| 11   | A3                | 75              | 10              | 7           | 0.06            | 0.0012          | 3.466           |
| 12   | A3                | 45              | 8               | 14          | 0.09            | 0.0015          | 7.087           |
| 13   | A3                | 15              | 6               | 21          | 0.35            | 0.0029          | 5.794           |
| 14   | A3                | 60              | 4               | 28          | 0.355           | 0.0038          | 9.437           |
| 15   | A3                | 30              | 2               | 35          | 0.265           | 0.0053          | 4.237           |
| 16   | A                | 30              | 4               | 7           | 0.25            | 0.0016          | 5.131           |
| 17   | A                | 75              | 2               | 14          | 0.35            | 0.0045          | 10.723          |
| 18   | A                | 45              | 10              | 21          | 0.175           | 0.0023          | 5.441           |
| 19   | A                | 15              | 8               | 28          | 0.215           | 0.0031          | 7.596           |
| 20   | A                | 60              | 6               | 35          | 0.285           | 0.0034          | 13.637          |
| 21   | C                | 15              | 2               | 7           | 0.385           | 0.0002          | 2.683           |
| 22   | C                | 60              | 10              | 14          | 0.175           | 0.0003          | 7.366           |
| 23   | C                | 30              | 8               | 21          | 0.36            | 0.0003          | 10.201          |
| 24   | C                | 75              | 6               | 28          | 0.3             | 0.0003          | 10.433          |
| 25   | C                | 45              | 4               | 35          | 0.31            | 0.0004          | 9.473           |
deviation values. If the problem has \( n \) responses, a matrix of \( nx1 \) was formed as depicted in equation (5) in this scenario, a matrix of \( 3 \times 1 \) has been constructed \[40\]. The weight of each criterion was determined by the ratio of these matrix values to the summation of all the values in the matrix as shown in equation \(6\) \[41\].

\[
Bij = \text{CORREL} (Ai1 Ai2 Aj1 Bj1 Bj2 Bij) \tag{4}
\]

\[
\{Bij = \text{CORREL} (A_{11}; A_{25}, A_{31}; A_{25})\}
\]

\[
\{B_{21} = -0.26087, B_{31} = -0.26181, B_{12} = -0.26087, B_{13} = 0.257715, B_{31} = -0.26181, B_{23} = 0.257715\}
\]

\[
Uij = \sigma ij \sum_{J=0}^{n} (1 - Bij) \tag{5}
\]

\[
\{1 - B_{21} = 1 - (1 - 0.26087) = 1.26087\}
\]

\[
\{\sum_{J=0}^{n} (1 - Bij) = (B_{11} + B_{21} + B_{31})\} = (0 + 1.26087 + 1.261814) = 2.522682\]

\[
U_{11} = 0.25328 * 2.522682 = 0.638946 \tag{6}
\]

\[
Wij = \frac{1 - U_{ij}}{\sum_{j=1}^{n}(1 - U_{ij})} \tag{5}
\]

\[
\{1 - U_{11} = 1 - 0.638946 = 0.361054\}
\]

\[
W_{11} = \frac{0.361054}{0.361054 + 0.336944 + 0.502304} = 0.301\}
\]

The next step consisted of forming a weighted normalised matrix generated from product of each criteria’s weight and normalisation matrix as depicted in equations (7) & (8). The next step was the calculation of assessment value which is the difference between the weighted normalised value of beneficiary attribute to the non-beneficiary attribute as shown in equation (9). The experiment with highest assessment value was taken as best parametric combination \[42\] as shown in table 4.
For beneficiaries

\[ V_{ij}^+ = W_{ij} * A_{ij} \]  

\[ V_{ij}^{+} = 0.301 * 0.15678 = 0.04719 \]

For Non - beneficiaries

\[ V_{ij}^- = W_{ij} * A_{ij} \]  

\[ V_{ij}^- = 0.418 * 0.0519 = 0.02169 \]

\[ Y_{ij} = \sum_{i=0}^{n} V_{ij}^+ - V_{ij}^- \]  

\[ Y_{ij} = ((0021694 + 2.27771 * 10^{-5}) - 0.04719) = 0.016997832 \]

In order to identify the best electrode material an alternative decision matrix \((Q_{ij})\) was formed according to the equation (10). It is the sum of all the values of the ith alternate’s weighted normalised decision matrix as shown in table 5. \(Q_{ij}\) was normalised and multiplied with criterion weight to form the weighted alternative decision matrix \((R_{ij})\) as shown in the equation (11).

\[ Q_{ij} = \text{Sum (} V_{ij} \text{)}, \text{ equal to (Alt (} i \text{), } X (i)) \]  

\[ Q_{ij} = 0.04719 + 0.066364 + 0.046086 + 0.025923 + 0.03733 = 0.180423 \]

\[ R_{ij} = W_{ij} * \left( Q_{ij} / \sum_{j=0}^{n} Q_{ij}^2 \right) \]  

\[ R_{ij} = 0.301 * \left( \frac{0.180423}{0.240287} \right) = 0.22609711 \]
The concordance element $C_{ij}$ was formed by comparing the performance measure of electrode with each other [43]. When the value of beneficiary response was higher than the alternative, the equivalent solution weight has been taken and the non-beneficiary criteria calculated vice versa as shown in equation (12). The alternative $A_1$ was compared with $A_2$ in such a way that $R_{11} > R_{12}, R_{21} > R_{22}$ and $R_{31} < R_{33}$. The value of $C_{11}$ was 0.719. Similarly all other alternatives are compared with each other as depicted in equation (13) and its value was shown in table 6. Following $\bar{C}$ was determined which was the average value of all non-zero element in the concordance set [44]. If the concordance element was higher than $\bar{C}$, the value was one or zero in concordance matrix $C_{ij}$, as shown in table 7.

$$C_{ij} = \frac{f[R_{ij} \geq R_{bj}]}{\binom{G_{12}}{C_{12}}} = \frac{(0.226009711 > 0.119912327),}{(0.127329 > 0.125748), (0.082899 < 0.13232)}$$

$$\{C_{12} = 0.301 + 0 + 0.418 = 0.719\}$$

$$C_{ij} = \begin{bmatrix} 0 & C(1, 2) & C(1, j) \\ C(2, 1) & 0 & C(2, j) \\ C(i, 1) & C(i, j) & 0 \end{bmatrix} \quad (13)$$

$C_{ij} > \bar{C}$, Then $C_{ij} = 1$ or $C_{ij} = 0$

$$\left\{ \bar{C} = \frac{8.144}{15} = 0.5429 \right\}$$

$$\{C_{12} = (0.719 > 0.5429) = 1\}$$

The ensuing stage was the calculation of the discordance element $D_{ij}$ as shown in equation (14). The discrepancy between the alternatives was computed and the value of discordance is the proportion between the most negative and the highest value [45]. For example to compute the element $D_{12}$ ($R_{11} - R_{21}$), $R_{12} - R_{22}$ and ($R_{13} - R_{23}$) was calculated. The ration of maximum negative value of these three elements to the maximum value among of these three elements was taken as $D_{12}$ as depicted in equation (15). Similarly $\bar{D}$ was the average value of all non zero elements in the discordance set [46] as shown in table 6. If the discordance element was higher than $\bar{D}$, the value was one or zero in discordance matrix $D_{ij}$, as shown in table 7.

$$D_{ij} = \frac{f[R_{ij} \geq R_{bj}]}{\binom{D_{12}}{D_{21}}} = \frac{\frac{\text{Max} (-a_{12})}{\text{Max} (a_{1} - a_{2})}}{\frac{\text{Max} (-b_{21})}{\text{Max} (b_{2} - b_{1})}} = \frac{\text{Max} (-n_{ij})}{\text{Max} (n_{i} - n_{j})}$$

$$\begin{cases} \text{Max} (-a_{12}) = -\text{Max} (0.22601 - 0.119912)(0.127392 - 0.125748)(0.082899 - 0.13232) = 0.466 \\ \text{Max} (a_{1} - a_{2}) = 0.106097 \end{cases}$$

$$\{D_{12} = (0.466 > 0.778) = 0\}$$

$D_{ij} > \bar{D}$, Then $D_{ij} = 1$ or $D_{ij} = 0$

$$\left\{ \bar{D} = \frac{14.78443}{19} = 0.778 \right\}$$

The final step was the aggregation of concordance and discordance matrix as per the equation (16) [47, 48]. The value of aggregation matrix was shown in table 8. From table it was inferred that A2 was the best electrode.
followed by A1 and C electrode. The best parametric combination obtained from MEIOT optimization technique was 60 μs pulse on time, 8 μs pulse off time and 7 A current machined using A2 composite electrode.

\[
S_{ij} = C_{ij} \times D_{ij} \\
\{S_{11} = C_{11} \times D_{11} = 0\}
\]

4. Results and discussion

4.1. Influence of process parameters on MRR

In EDM machining occurs because of melting and vaporization [49]. Owing to this the materials removed from the work piece as well as from the electrode. The industry demanded a low EWR and a high MRR, as well as an excellent surface quality. The MRR rises with increasing current as it facilitates the melting an evaporation [50] until the saddle point, beyond this limit it triggers energy destabilization [51] which reduces the MRR as shown in figure 1. Destabilization occurs at different point for distinct electrodes, for electrodes A and A1, it was 14A, and for electrodes A2, A3, and C, it was 21 A. Of the five different electrode A1 composite tool offers highest
Figure 3. Main effect plot of $R_a$ versus (i) Material type (ii) Pulse on Time (iii) Pulse off time (iv) IP Current.

Figure 4. Surface Topography of Ti4Al6V alloy machined with Copper electrode (a) At lower magnification (b) At Higher Magnification.
MRR. As discussed earlier while machining some of the materials were removed from the electrode surface, owing to this the graphite particles get detached from the surface and enter inside the spark gap. When a voltage was applied to these particles, they become energized and travel in a zigzag pattern [52, 53], resulting in the bridging effect. It generates multiple discharges in a single flash, which results in faster sparking and impoverishment of the workpiece surface [54, 55]. With increase in graphite content the MRR reduces owing to the occurrence of short circuit. when machined with a standard C electrode, it has a lower MRR than A1 but a higher MRR than other electrodes used for experimentation. When machined with composite tool, the MRR decreases as the pulse on time increases, which contradicts the pattern found by other researchers [56, 57]. Because of the bridging effect, higher discharge energy and spark intensification occur at lower pulse on time. The plasma channel widens [58] as the pulse on time increases until it reaches a saddle point of 45 s, reduces MRR. For each additional increment above 45 s, plasma channel densification happens, which increases MRR. As C and A were used as electrodes, MRR increased until it reached a svec, after which it began to decrease, as observed by several researchers. The MRR decreases with increase in pulse off time owing to the reduction in discharge energy. The highest MRR was observed when the sparking time was 3.75 μs per cycle.

5. Influence of process parameters on EWR

The electrode with the highest melting temperature has the lowest EWR [59], which was well correlated with the results that the copper tool with a melting temperature of 1085 °C has the lowest EWR as compared with aluminium electrodes as depicted in figure 2. Interestingly the EWR was reduced when graphite was added as

![Figure 5. Surface Topography of Ti4Al6V alloy machined with A1 Composite electrode (a) At lower magnification (b) At Higher Magnification.](image-url)
reinforcement. Due to the tiny arcs that occur during production, the intensive movement of electrons will reverse the feed path to maintain an even greater chimney gap [60]. The EWR value could then be lowered quickly since most negative ions pass into the phase breakdown [61]. The EWR raises with increase in discharge current owing to the higher spark intensity. When A1 was used as an electrode, it had the lowest EWR with increasing current as compared to other composite tools due to complete heat dissipation because of increment in spark gap [62]. Owing to the short circuit, A2 and A3 have a higher EWR. The EWR decreases as the pulse on time increases until it reaches a tush point of 45 s. As previously mentioned, the materials extracted from the electrode were relegated as a result of the decrease in spark power [63]. The plasma densification evaporated the tool metal beyond the tush limit, increasing EWR. The Electrode machined with a pulse off time 2 $\mu$s possesses highest EWR as it declines sharply when the parametric value was set at 4 $\mu$s thereafter it increases gradually with increase in pulse off. The least EWR was achieved when the off time was kept at 7.5 $\mu$/cycle.

6. Influence of process parameters on $\text{Ra}$

The surface quality of the product worsens with increase in the input current as depicted in the graph. When the current was 7A, the products are manufactured with the average Ra value of 2.699 $\mu$m and it was drastically increased to 6.527 $\mu$m when the discharge current was tuned to 14A. The Ra value increased with discharge current regardless of the electrode used as shown in figure 3. This was attributed to the fact higher current produces high spark intensity [64] which creates deep craters and crack on the surface hence surface quality reduces [65]. The EDM process machined the metal with superior surface quality when the parametric value of pulse on time was set to 30 s. The transformation from good to bad surface happens when the unit is tweaked to sufficient.
45 s, and it worsens with further increase in parametric value. This was ascribed by the fact multiple discharge in single flash creates cracks on the surface, many researchers reported the similar findings [66–68]. With increasing pulse off time, the Ra value increases until a saddle point of 4 μs further begins to decrease. The electrode A and C produces the material of higher Ra value, it was drastically reduced when graphite was added to aluminium. While machining the particles that present inside the eroding area increases the spark gap. Hence the melted material are completely flushed away from the surface which eliminates the formation of remelted layer on the surface [69]. With increase in weight percentage of graphite particles more foreign particles hang in the spark gap which hinders short circuit, hence Ra value increases [70]. Manufacturing titanium implants with the mirror surface finish was the ultimate objective of the work. When machined utilizing A2 tool at the discharge current of 7A a minimum surface roughness value of 0.847 μm was attained.

7. Surface topography

The surfaces of the titanium alloy machined using the tools A1, A2 and C having surface roughness of 1.37, 0.847 and 2.683 μm respectively was investigated using SEM. The surface topography of titanium alloy machined with copper tools showed black spots, craters and micro pits as shown in figure 4(a). The surface also displayed remelted layer which occurs because of incomplete flushing. At higher magnification the surface topography showed micro cracks, deeper craters and uneven fusion structures as shown in figure 4(b). It was evident that the heat was not completely dissipated when copper was used as an electrode. Pockmarks were observed on the surface which was formed due to the release of entrapped gas during the cooling phase.

The occurrence of eczema on the EDMed work surface obtained with the A1 composite tool electrode was a notable feature as shown in the figure 5(a). This eczema was white in colour and spherical in shape and spread all over the surface. Apart from that machined surface showed globules and scratches. At higher magnification this eczema appeared as the lot of tiny remelted layer as shown in figure 5(b). Owing to this A1 composite tool offers 61% worsen surface as compared with A2 tool. Micro pits and globules were also observed on the surface.

The surface topography of the titanium alloy machined with A2 composite alloy showed black spots and minute scratches as shown in figure 6(a). The black spots are formed owing to the deposition of carbon content from the dielectric fluid. Pits, craters and cracks were not formed on the surface which reveals that the heat was completely removed from the machined area owing to the increase in spark gap. The formation of remelted layer was controlled to a greater extent but was not completely eliminated. It showed some melted materials are redeposited over the surface during the colling phase. At higher magnification the surface texture showed globules, remelted layer and wrinkled shape as shown in figure 6(b). This wrinkled shape was formed due to the release of debris from the electrode material. As more flashes occurred in a single cycle which results in the formation of globules.

8. Conclusion

The aim of the work was to achieve the best surface quality of titanium implants, for which composites tools as well as traditional tools were used. Five electrodes namely copper, aluminium and aluminium reinforced with graphite particles of 5, 10 and 15 weight percentage fabricated using stir casting technique were employed for EDM. The impact of discharge current, pulse on time and pulse off time over MRR, EWR and Ra were analysed and following conclusions were drawn.

1. Maximum MRR was achieved due to the bridging effect when A1 composite tool was used as electrode; however, as the weight percentage of graphite increases, MRR decreases due to the occurrence of short circuit. The copper tool with the highest melting point among the chosen electrodes has the lowest EWR. Owing to the increase in spark gap the Ra value decreases when A2 composite tool was used as electrode.

2. MRR improves with increase in current intensity until a saddle point, thereafter it declines because of energy destabilization. Higher pulse on time causes plasma channel expansion, which lowers MRR, while lower pulse on time causes plasma intensification that improves MRR. The discharge energy decreases as the pulse off time increases, resulting in a lower MRR.

3. Because of the increased spark intensity, the EWR increases as the discharge current increases. EWR increases due to plasma densification with increased pulse on time. Ra roughness increases with increase in discharge current and pulse on time. When composite tools are used, debris is totally flushed away due to the increase in spark gap, which prevents re-solidification of materials over the surface, which improves Ra.
(4) The surface topography showed black spots, globules and redeposited particles which were absent on the surface machined using A2 composite tool. Eczema like surface was observed when A1 composite tool was used, at higher magnification it was revealed as the cluster of tiny remelted layer. A2 machined surface showed black spots and globules, formation of remelted was prevented owing to comprehensive heat removal which improves Rz.

(5) MEIOIT optimisation technique was utilized to select the best parametric combination and electrode material. Titanium alloy machined with parametric value of 60 μs pulse on time, 8 μs pulse off time and 7A current machined using A2 composite electrode increases productivity.

**Data availability statement**

All data that support the findings of this study are included within the article (and any supplementary files).

**ORCID iDs**

Ranjith R [https://orcid.org/0000-0001-5278-5039](https://orcid.org/0000-0001-5278-5039)

**References**

[1] Barbieri M, Mencio F, Papiri P, Rosella D, Di Carlo S, Valente T and Pompa G 2017 Corrosion behavior of dental implants immersed into human saliva: preliminary results of an in vitro study European review for medical and pharmacological sciences 21 3543–8

[2] Kumar P B and Parhi D R 2017 Vibrational characterization of a human femur bone and its significance in the designing of artificial implants World Journal of Engineering. 14 222–226

[3] Gulati K, Pradeaux M, Kogawa M, Lima-Marques L, Atkins G J, Findlay D M and Losic D 2017 Anodized 3D-printed titanium implants with dual micro-and nano-scale topography promote interaction with human osteoblasts and osteocyte-like cells J. Tissue Eng. Regen. Med. 11 3313–25

[4] Lewin S, Åberg J, Neuhaus D, Engqvist H, Ferguson S J, Ohman-Magi C and Persson C 2020 Mechanical behaviour of composite calcium phosphate–titanium cranial implants: Effects of loading rate and design J. Mech. Behav. Biomed. Mater. 104 103701

[5] Wang Z, Zhou R, Wen F, Zhang R, Ren L, Teoh S H and Hong M 2018 Reliable laser fabrication: the quest for responsive biomaterials surface J. Mater. Chem. B 6 3612–31

[6] de Aguiar K M R, Alves V S, Noeske P L M, Rischka K, Portela M B, Ferreira-Pereira A and Rodrigues-Filho U P 2019 Hybrid films based on nonisocyanate polyurethanes with antimicrobial activity InMaterials for biomedical engineering (Amsterdam: Elsevier) 77–116

[7] Mesa-Restrepo A, Civanatos A, Allain J P, Patiño E, Alzate J F, Balcázar N and Torres Y 2021 Synergistic effect of rhBMP-2 protein and nanotextured titanium alloy surface to improve osteogenic implant properties Metals 11 464

[8] Zakaria M Y, Sulong A B, Ramli M I and Raza M R 2017 Determination of critical powder loading of titanium–hydroxyapatite with powder–space holder for powder injection molding feedstocks Journal of Mechanical Engineering (JMechE) 11 11–21

[9] Ranjith R, Tamilselvam P, Prakash T and Chinnasamy C 2019 Examinations concerning the electric discharge machining of AZ91/5B (4Cr)P) composites utilizing distinctive electrode materials Mater. Manuf. Processes 34 1120–8

[10] Al-Amin M, Abdul Rani A M, Abdu Aliyu A A, Abdul Razak M A H, Hastuty S and Bryant M G 2020 Powder mixed-EDM for potential biomedical applications: A critical review Mater. Manuf. Processes 35 1789–811

[11] Singh S K and Mali H S 2019 Effect of different electrodes on micro-feature fabrication in biomedical Co–29Cr–6Mo alloy machined using μ-EDM process. Advances in Micro and Nano Manufacturing and Surface Engineering (Singapore: Springer) pp. 249–57

[12] Ranjith R, Giridharan P K and Devaraj J 2018 Sensitivity analysis and optimization of EDM process parameters using response surface methodology Mater. Manuf. Processes 33 397–404

[13] Ragavendran U, Ghadai R K, Bhui A K, Ramachandran M and Kalita K 2018 Sensitivity analysis and optimization of EDM process parameters Transactions of the Canadian Society for Mechanical Engineering 43 13–25

[14] Li X, Yan F, Ma J, Chen Z, Wen X and Cao Y 2019 RBF and NSGA-II based EDM process parameters optimization with multiple constraints Math. Biosci. Eng. 16 5788–803

[15] Dhamkar K, Chaudhary K, Drivedi A and Bemblade O 2019 An environment-friendly and sustainable machining method: near-dry EDM Mater. Manuf. Processes 34 1307–15

[16] Marichamy S, Saravanan M, Ravichandran M and Stalin B 2017 Optimization of surface roughness for duplex brass tool in EDM using response surface methodology Mechanics and Mechanical Engineering 21 57–66

[17] Choudhary R, Singh G, Kumar K, Bharti P, Kumar R and Kumar V 2018 Investigations of electrical discharge machining of Al6061/14% wt fly-ash composite with different tool electrodes Mater. Today Proc. 5 19923–32

[18] Raza M H, Wasim A, Ali M A, Hussain S and Jahanzaib M 2018 Investigating the effects of different electrodes on Al6061–SiC 7.5 wt% during electrical discharge machining Int. J. Adv. Manuf. Technol. 99 3017–34

[19] Ramesh S and Jenarthanan M P 2018 Investigating the performance of powder mixed electric discharge machining of nimonic 75 by using different tool materials World Journal of Engineering. 15 205–215

[20] Kumar S, Datta S, Masanta M, Nandi G and Pal P K 2018 Electro-discharge machining of Inconel 825 super alloy: effects of tool material and dielectric flushing Silicon 10 2079–99

[21] Payal H and Sharma S K 2019 Study of MRR and TWR in electric discharge machining of AISI D2 tool steel IntAdvances in Industrial and Production Engineering (Singapore: Springer) pp 85–92

[22] Ramesh S, Jenarthanan M P and AS B K 2018 Experimental investigation of powder-mixed electric discharge machining of AISI P20 steel using different powders and tool materials Multidiscipline Modeling in Materials and Structures. 14 549–566
Bhaumik M and Maity K 2018 Effect of different tool materials during EDM performance of titanium grade 6 alloy Engineering Science and Technology, an International Journal 21 507–16

Singh S, Maheshwari S and Pandey P C 2004 Some investigations into the electric discharge machining of hardened tool steel using different electric discharge machining J. Mater. Process. Technol. 149 272–7

Payal H, Bharti P S, Maheshwari S and Agarwal D 2020 Machining characteristics and parametric optimisation of inconel 823 during electric discharge machining Tehnički vjesnik 27 761–72

Kutlu Gundogdu F and Kahraman C 2019 Spherical fuzzy sets and spherical fuzzy TOPSIS method Journal of intelligent & fuzzy systems 36 337–52

Mete S 2019 Assessing occupational risks in pipeline construction using FMEA-based AHP-MOORA integrated approach under Pythagorean fuzzy environment Human and Ecological Risk Assessment: An International Journal 25 1645–60

Achebo J and Odinikuku W E 2015 Optimization of gas metal arc welding process parameters using standard deviation (SDV) and multi-objective optimization on the basis of ratio (MOORA) Journal of Minerals and Materials Characterization and Engineering 3 298

Khajuria A, Bedi R, Singh B and Akhtar M 2018 EDM machinability and parametric optimisation of 2014Al alloy using full factorial design approach International Journal of Machine Tools & Manufacture 122 76–82

Verma V and Sahu R 2017 Process parameter optimization of die-sinking EDM on Titanium grade Ti6Al4V using full factorial design approach Manuf. Processes 35 1336–32

Chen L and Pan W 2018 Fuzzy set theory and extensions for multi-criteria decision-making in the construction industry International Journal on Hybrid Intelligent Systems 11 31–43

Singh S, Maheshwari S and Agarwal D 2020 Machining characteristics and parametric optimisation of inconel 823 during electric discharge machining Tehnički vjesnik 27 761–72

Feng F, Xu Z, Fujita H and Liang M 2020 Enhancing PROMETHEE method with intuitionistic fuzzy soft sets Int. J. Intell. Syst. 35 1071–104

Wang L, Yin K, Cao Y and Li X 2019 A new grey relational analysis model based on the characteristic of inscribed core (IC-GRA) and its application on seven-pilot carbon trading markets of China International journal of environmental research and public health 16 99

Kutlu Gundogdu F and Kahraman C 2019 Extension of WASPAS with spherical fuzzy sets Informatica 30 269–92

Paul T R, Saha A, Majumder H, Dey V and Dutta P 2019 Multi-objective optimization of some correlated process parameters in EDM of Inconel 800 using a hybrid approach Journal of the Brazilian Society of Mechanical Sciences and Engineering 41 1–11

Achebo J and Odinikuku W E 2015 Optimization of gas metal arc welding process parameters using standard deviation (SDV) and multi-objective optimization on the basis of ratio (MOORA) Journal of Minerals and Materials Characterization and Engineering 3 298

Khan A and Maity K P 2016 Parametric optimization of some non-conventional machining processes using MOORA method Int. J. Eng. Res. Adv. 20 (Switzerland: Trans Tech Publications) 19–40

Chakraborty S 2023 Multi-objective optimization of EDM process on AISI P-20 Tool steel using multi-criteria decision-making technique In Machine Learning Applications in Non-Conventional Machining Processes (Hershey, Pennsylvania, USA: IGI Global) pp. 33–44

Rencber O F 2019 Gri Biğisel Analiz ve VİKOR Yöntemlerinin Karslaştırma: İmalat Sektörü Üzerine Önem Bir Uygulama Journal of Yaşar University 14 69–81

MTC customer satisfaction model in automotive industry using ANP approach Advanced Manufacturing 2 2020 11 177–86

Sharma A, Belokar R M and Kumar S 2017 Optimization of gas protected stir casting process using GRA and TOPSIS International journal of engineering & materials sciences 24 437–46

Degasperi A, Fey D and Kholodenko B N 2017 Performance of objective functions and optimisation procedures for parameter estimation in system biology models NPI systems biology and applications 3 1–9

Akram M, Luqman A and Alcantud J C R 2020 Risk evaluation in failure modes and effects analysis: hybrid TOPSIS and ELECTRE I solutions with Pythagorean fuzzy information Neural Computing and Applications 33 1–29

Žižović M, Miljković B and Marinković D 2020 Objective methods for determining criteria weight coefficients: A modification of the CRITIC method Decision Making: Applications in Management and Engineering 3 149–61

Kustiyaningsih Y, Sophan K, Ummah N R and Piramana J 2021 MCGDM for selection of OSM participants using integration AHP and MOORA methods. In J. Phys. Conf. Ser. (Bristol: IOP Publishing) 1836021037

Paul T M, Roumpos C and Pavloubakis F 2020 A multi-criteria approach for the evaluation of low risk restoration projects in continuous surface lignite mines Energies 13 2179

Schaefer J L, Fagundes B J, Moraes J, Nara E O B and Kothe J V 2019 Aplicação de métodos multicritério para ordenação e comparação da eficiência financeira dos clubes de Futebol do campeonato brasileiro de Futebol do sêrie a Revista Brasileira de Futebol e Futebol 11 31–43

Xu G L. 2018 A consensus reaching model with minimum adjustments in interval-valued intuitionistic MAGDM Mathematical Problems in Engineering 2018 9078613

Bai C, Kusi-Sarpong S, Badri Ahmed H and Sarkis J 2019 Social sustainable supplier evaluation and selection: a group decision-support approach Int. J. Prod. Res. 57 7046–67

Chen L and Pan W 2018 Fuzzy set theory and extensions for multi-criteria decision-making in construction management In Fuzzy Hybrid Computing in Construction Engineering and Management. (West Yorkshire, England: Emerald Publishing Limited.) 179–228

Amr S H, Abdulballeh A and El Ouazzani Y 2018 Interactive facility layout problem: a bi-objective design International Journal on Interactive Design and Manufacturing (IJIDeM) 12 151–9

Yadv V K, Kumar P and Drivedi A 2019 Effect of tool rotation in near-dry EDM process on machining characteristics of HSS Mater. Manuf. Processes 34 779–90

Mandal P and Mondal S C 2019 Surface characteristics of mild steel using EDM with Cu-MWCNT composite electrode Mater. Manuf. Processes 34 1332–32

Pradnya Y R A, Ferrara A, Aminuddin A, Wahono W and Jang J S C 2020 The effect of discharge current and pulse-on time on biocompatible Zr-based BMG sinking-EDM Open Engineering 10 401–7

Khajuria A, Bedi R, Singh B and Akhtar M 2018 EDM machinability and parametric optimisation of 2014Al/Al2O3 composite by RSM Int. J. Mach. Mach. Mater. 20 536–55

Verma V and Sahu R 2017 Process parameter optimization of die-sinking EDM on Titanium grade–V alloy (Ti6AhV) using full factorial design approach Mater. Today Proc. 4 1893–9

Faisal N and Kumar K 2018 Optimization of machining process parameters in EDM for EN 31 using evolutionary optimization techniques Technologies 6 54

Singh G, Lamichhane Y, Bhui A S, Sidhu S S, Bains P S and Mukhiya P 2019 Surface morphology and microhardness behavior of 316L in HAp-PMEDM Faca Universitatis, Series: Mechanical Engineering 17 445–54

Singh M A, Rajbongshi S K, Sarma D K, Hanzel O, Sedláček J and Saigalik P 2019 Surface and porous recast layer analysis in μ-EDM of MWCNT-Al2O3 composites Mater. Manuf. Processes 34 567–79

Mazarbhuiya R M, Dutta H, Debnath K and Rahang M 2020 Surface modification of CFRP composite using reverse-EDM method Surfaces and Interfaces 18 100457

Dey A, Datta S, Moyez S A, Kamila A, Mukherjee K and Roy S 2021 Blending of dielectric perovskite with electron transport materials: a case study towards improving bio-molecular devices for energy harvest ECS Journal of Solid State Technol. 10 013003
[59] Li S, Yin X, Jia Z, Li Z and Han L 2020 Modeling of plasma temperature distribution during micro-EDM for silicon single crystal Int. J. Adv. Manuf. Technol. 107 1731–9
[60] Dang X P 2018 Constrained multi-objective optimization of EDM process parameters using kriging model and particle swarm algorithm Mater. Manuf. Processes 33 397–404
[61] Liang J F, Liao Y S, Kao J Y, Huang C H and Hsu C Y 2018 Study of the EDM performance to produce a stable process and surface modification Int. J. Adv. Manuf. Technol. 95 1743–50
[62] Ky L H, Danh B T, Cuong N V, Hong T T, Nguyen T V, Nguyen T Q D and Nguyen M C 2020 Effect of input parameters on electrode wear in PMEDM cylindrical shaped parts Key Eng. Mater. 863 (Switzerland: Trans Tech Publications) 136–42
[63] Le Q D, Nguyen H P, Banh T L and Nguyen D T 2020 Comparative study of low-frequency vibrations assigned to a workpiece in EDM and PMEDM Int. J. Mod. Phys. B 34 2040145
[64] Ahmad S, Lajis M A, Haq R H A, Ariffin A M T, Rahman M N A, Haw H F and Abdullah H 2018 Surface roughness and surface topography of Inconel 718 in powder mixed dielectric electrical discharge machining (PMEDM) International Journal of Integrated Engineering 10
[65] Hong T T, Danh B T, Cuong N V, Ky L H, Linh N H, Nga N T T and Cuong N M 2021 A study on influence of input parameters on surface roughness in PMEDM cylindrical shaped parts Mater. Sci. Forum 1018 (Switzerland: Trans Tech Publications) 65–70
[66] Le V, Banh T, Tran X and Nguyen T H M 2019 Improving surface roughness by electrical discharge machining with tungsten powder ASEAN Engineering Journal 9 84–53
[67] Tran T H, Nguyen M C, Luu A T, Le T Q, Vu T T, Tran N G and Vu N P 2020 Electrical discharge machining with SiC powder-mixed dielectric: an effective application in the machining process of hardened 90CrSi steel Machines 8 36
[68] Sahu D R and Mandal A 2020 Critical analysis of surface integrity parameters and dimensional accuracy in powder-mixed EDM Mater. Manuf. Processes 35 430–41
[69] Patel S, Thesiya D and Rajurkar A 2018 Aluminium powder mixed rotary electric discharge machining (PMEDM) on Inconel 718 Australian Journal of Mechanical Engineering 16 21–30
[70] Le V T 2021 Influence of processing parameters on surface properties of skd61 steel processed by powder mixed electrical discharge machining J. Mater. Eng. Perform. (https://doi.org/10.1007/s11665-021-05584-9)