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Multi-Response Optimization-Based WEDM Process for Enhancing the Machining Properties of Ti-6Al-4V and Al6061

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***Abstract:* -** Ti-6Al-4V and Al6061 are alloys known for their excellent strength-to-weight ratio. Standard processing procedures find these alloys to be difficult and complex, despite their good properties. The creation of complicated and complex geometries, which is challenging using standard processes, requires nonconventional approaches. In this research, wire electrical discharge machining (WEDM)'s potential applications are utilized for enhancing and analysing the machining properties of Ti-6Al-4V and AA6061. To maximize Material Removal Rate (MRR) and minimize Surface Roughness (SR), it is necessary to optimize several process parameters. Combining Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) with Grey Relational Analysis (GRA) allows for the optimization of a large number of parameters. Based on the findings, the ideal settings for cutting Al6061 grade steel are as follows: 80V, 700 RPM wire speed, 2 A maximum current, 20 µs pulse on time (TON), and 15 µs pulse off time (TOFF). With a minimal Dimensional Deviation (DD) of 0.04 and an ideal SR value of 1.01 Ra, the results are satisfactory. The ideal settings for cutting Ti-6Al-4V include a voltage of 80V, a wire speed of 1400 RPM, a maximum current of 4 A TON for 40 µs, a TOFF of 25 µs, and a steady current of 4 A. With these particular settings, the smoothest surface is achieved with a SR of 1.9 Ra and a DD of 0.08.

Keywords: Grey Relational Analysis, TOPSIS, WEDM, Aluminium 6061, Titanium grade 5.

I. INTRODUCTION

WEDM is an electrothermal machining technique that removes material through the degrading of metal particles that have been taken from the substrate by high-intensity sparks of electricity that are applied to the metallic wire [1-2]. In electrolytic deposition manufacturing, the material and the slicing tool are both immersed in the di-electric solution [3-4]. The dielectric fluid is continuously drained and filtered to whittle away at the particles [5]. The WEDM is widely used in the automotive, aerospace, and tooling industries for the fabrication of accurate components [6]. The standard machining procedures can be rather challenging when it comes to fabricating intricate geometrical pieces out of materials that are tough to machine [7-8]. The WEDM, on the other hand, adeptly overcomes these challenges with remarkable efficiency and precision. Hence, this approach has emerged as a very auspicious area of study during the last several decades, and many researchers have extensively explored it for parameter optimization [9-10]. Ti-6Al-4V and Al6061 present one-of-a-kind opportunities and challenges for the WEDM process because the diverse material qualities of these two materials require careful attention during the optimization process [11-12]. Figure 1 shows the schematic illustration of the WEDM process.

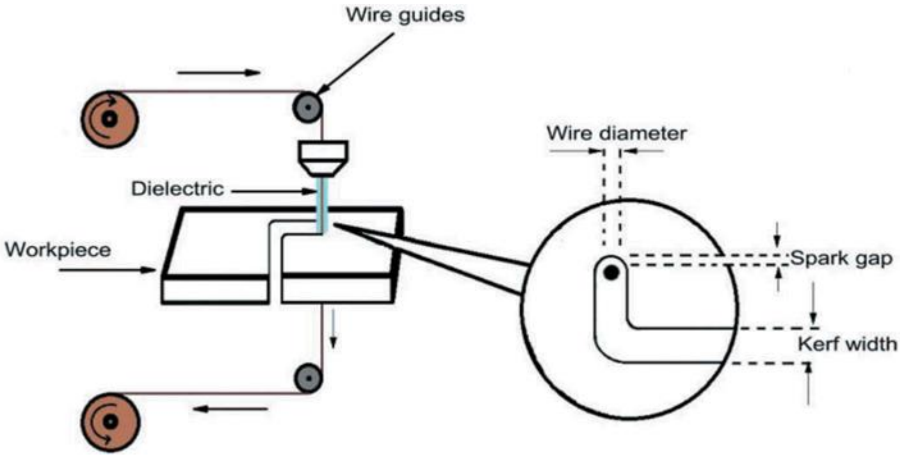

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Figure 1. Schematic design of the WEDM process [13]

A. Material selection for the WEDM process: Aluminium alloy and titanium Alloy

Material selection is an extremely important aspect of the WEDM process, especially when working with complex alloys such as aluminium and titanium [14]. Both the aviation and automobile industries make substantial use of aluminium alloys because of their reputation for having qualities that make them lightweight [15-17]. In addition to this, aluminium alloys are well known for their suitability for high-speed machining, which makes them excellent for the production of complicated components [18].

Titanium alloys, such as Ti-6Al-4V, possess an exceptional strength-to-weight ratio and exhibit resistance to corrosion. Consequently, they are extensively used in the aerospace and healthcare sectors [19-20]. However, careful consideration is required when using WEDM because of the inherent difficulties associated with the machinability of Ti-6Al-4V [21]. Because it is a non-contact technique, WEDM reduces the likelihood of inflicting mechanical strain on titanium components and the precision of the process makes it easier to create complicated forms [22-23]. The choice of aluminium and titanium alloys illustrates the need to strike a strategic balance between the demands of lightweight design and the requirement for the development of precise machining skills in contemporary production processes [24-25]. Figure 2 shows the test specimen of Titanium and Aluminium Alloy.

(a) Ti-6Al-4V (b) Al 6061

Figure 2 Test specimen of Titanium and aluminium alloy [26-27]

To investigate potential solutions to the complex problems that arise during the WEDM operation when applied to Ti-6Al-4V and Aluminium alloy is the goal of this research. The formulation of the problem centres on the necessity of determining the ideal settings for the parametric variables to enhance the efficacy of the machining process while considering several responses. These responses include the Material Removal Rate (MRR) and the Surface Roughness (SR). Effectively utilizing WEDM with Ti-6Al-4V and Al6061 demands a tailored approach due to their distinct material properties and characteristics [28]. The plan is to use a GRA and TOPSIS-based multi-response optimization technique. GRA aids in investigating the connections between the answers and reveals the optimal parameter combinations. Comparatively, TOPSIS facilitates the selection of optimal settings. Understanding the WEDM process for Ti-6Al-4V and Al6061, in general, is the goal of the research.

The subsequent sections of the paper are structured in the following manner: Section 2 provides an overview of the literature review conducted by previous authors. Section 3 delves into the materials and techniques utilized in this research, providing a detailed explanation of their implementation. Section 4 presents the obtained results. Finally, section 5 concludes by summarizing the findings of the research and discussing the future scope of this study.

II. LITERATURE REVIEW

This section discusses the previous work done in the area of parametric Optimization of WEDM processes using various materials including titanium alloy and Aluminium alloy based on methods. In 2023, Paulson et al. [29] conducted a sequence of studies on Ti-6Al-4V to ascertain the impact of various machining settings in WEDM. The investigation used the Taguchi approach and the GRA method from the Minitab 18 program. At a peak current of 3 A, the outcomes revealed that a TON of 30s and TOFF of 9s provided the optimum overall output values for

MRR and Minimum SR. Previously, Juliyana et al. in 2023 determined the wire cut EDM optimal settings for the created LM5/ZrO2/Gr composite, and the results of this study were analysed using GRA. According to the results of the experiments and the GRA, the optimal process characteristics for obtaining the highest grey relational score are a ratio of 6% ZrO2 to 2% graphite reinforcement [30].

However, in 2023, Adedeji et al. suggested a robust approach for evaluating the desirability function using a combination of Taguchi Pareto Gray wolf optimization. The suggested technique was efficient because of the little data required to enhance the wire EDM process parameters for nitinol [31]. In 2022, Arya and Singh [32] proposed a metaheuristic strategy combined with the response surface technique to enhance several conflicting outputs during the processing of Incoloy 800H using WEDM. The data indicate that the TON was the primary factor in selecting which element had the most significant effect on the Reducing Frequency. Kumar et al. [33] in the same period (2022) work on getting the ideal set of processing variables for wire-EDM for a unique hybrid Aluminium matrix composite.

The optimization process started with the Taguchi method and then moved on to the TOPSIS method for doing multiple objective optimizations. It has been suggested that the optimal set of input variables for achieving optimal levels of SR, MRR, and Radial Overcut (ROC) is the following: 150A of current and 125s of pulse duration. Nevertheless, Doreswamy et al. in 2022 investigated the influence that different control parameters, such as current Ton and Toff, have on the MRR of machining Ti-6Al-4V alloy. According to the findings of the study, a change in the amount of current from 2 A to 6 A resulted in a large rise in MRR by 93.27%, and a change in the amount of time from 20 milliseconds (ms) to 35 ms improved MRR by 7.98%. Furthermore, a regression model was created to anticipate the MRR concerning the control parameters. This model exhibited a good forecast with an R2 value of 99.67%, which indicates that the model is accurate [34].

Riel and Lauwers (2022) in [35] suggested wire electrochemical processing as a refining technique as it works similarly to WEDM mechanically and eliminates conductive substances without harming the machined surface. Performed on a WEDM machine, the procedure improved machining productivity and the precision of the final products by doing away with reclamping. Obtaining removal depths larger than 20μ m with an SR below 1μm Ra demonstrates experimentally that wire-based electrochemical machining is a realistic method. Kumar et al. (2021) performed process parameter optimization utilizing the Taguchi grade planning concept of the L16 orthogonal array for WEDM of D2 steel [36]. It has been discovered that the most significant influence on MRR during WEDM comes from the current, whereas the flushing force has the least significant influence on MRR. During the WEDM process, the SR of a D2 steel workpiece is affected the most by wire speed, while the spacing voltage has a minimal impact on the SR of the workpiece.

Nevertheless, Ramaswamy et al. estimated the ideal set of process variables to obtain the lowest SR, and highest MRR using RSM in 2021 [37]. The findings showed that process parameter interactions have a major influence on SR, whereas Pon shows an effect on MRR. Meanwhile, in the same year (2021) Phate et al. [38] focused on using principal component analysis to enhance the WEDM process in a multi-response manner. The study used Taguchi's L18 mixed design and included MRR and SR as response variables. In summary, the most critical factors for the process are the percentage content of silicate, the Poff, and the current. However, Subburaj et al. [39] performed process-parameter improvement of a WEDM method in 2021. Taguchi's Design of experiment (DOE) was utilized to get a conclusion regarding the appropriate number of tests to conduct. The experimental results show that the maximum MRR rate achieved is 19.896 and a minimum SR of 0.333 Ra is achieved. Nevertheless, Aldurobi et al. (2020) developed a model using an artificial neural network to forecast the MRR and SR values for the processing of AlSi 1045 steel [40].

To attain its research goals, this study used variance analysis and the Taguchi technique. The results of this study indicate that the suggested model, which forecasts SR and MRR with an accuracy of around 98.136% and 97.3%, respectively, is the most accurate framework available. However, previously Soundararajan et al. (2020) [41] developed metal matrix composites using the Al6061 alloy by the stir cum squeeze casting method. The actual data shows that the mathematical model has outstanding predictive power, with average error readings within 6.47% for MRR and 1.52% for SR, which are considered acceptable. Majumder et al., (2020) [42] optimized the primary process parameters for multiple conflicting reactions during Inconel 718 WEDM using ratio estimation and multifaceted selection assessment. These machine settings are appropriate for multi-performance: Toff lasts 46 seconds, Ton 120 seconds and current 230 Amperes. While Thangaraj et al. (in 2020) proposed a decision-making technique for the intake process components using Taguchi-Grey analysis. The choice of the electrode made of wire was shown to have the most significant influence on the quality measurements in the WEDM procedure. The suggested technique has determined the optimal arrangement of the input parameters for the process, which includes the following parameters: duty factor (0.6), current at discharge (15 A), and gap potential (70 V) [43].

III. MATERIALS AND METHODS

1. In this section, the investigation's preparation of specimens and experimental setup, as well as the DOE, measurements of the response parameter, and optimum approach are explained in detail.

B. Materials

This study focused on Titanium and Aluminium alloys. Titanium alloy is popularly used in aerospace and biomedical applications. The selected aluminium alloy's versatility and low weight make it a popular material in the aerospace and transportation sectors. Tables 1 and 2 discuss the chemical composition, and Table 3 discusses the mechanical properties of both Ti-6Al-4V and aluminum alloy.

Table 1 Chemical composition of Ti-6Al-4V [44]

Chemical composition (%)	6.0	4.0	0.08	0.05	0.2	0.0125	0.3	Remaining
Elements	Al	V	C	N	O	H	Fe	Ti

Table 2 Chemical composition of Al6061 [45]

Chemical composition (%)	97.9	1.0	0.60	0.28	0.20
Elements	Al	Mg	Si	Cu	Cr

Table 3 Meechanical properties of Al6061 and Ti-6Al-4V

Properties	Ti-6Al-4V	Al6061
Density	4.429gm/cm3	2.7gm/cm3
Tensile strength	950MPa	124-290 MPa
Melting point	1604-1660	5850C
Thermal conductivity	6.7	173W/Mk
Young’s modulus	115GPa	68GPa
Poisson’s ratio	0.34	0.33
Modulus of elasticity	113.8	70-80GPa

C. *Design of Experiments*

In order to investigate the influence that wire-EDM has on MRR, specific parameters including current, P_{on} and P_{off} time, wire speed, and voltage have been chosen. The wire-EDM process parameters, as well as the settings that were chosen for them, are detailed in Table 4. The results of the tests and experiments were used to determine these levels. Table 5 discusses the WEDM process parameters and their values.

Table 4 Dimensions of the workspaces

Dimension	Value (cm)
Length	2.5
Breadth	2
Height	0.8

Table 5 Wire-EDM process parameters and settings

Characteristic	Unit	Level 1	Level 2	Level 3	Level 4
Max current	A	2	3	4	5
Ton	μ sec	20	30	40	50
Toff	μ sec	10	15	20	25
Wire-speed	RPM	175	350	700	1400
Voltage	V	80	90	-	-

D. *TOPSIS*

TOPSIS is a technique of making decisions that ranks potential solutions based on how close they are to the optimal answer in the fields of engineering and manufacturing. Within the framework of WEDM, it can assist in identifying the ideal set of process variables for Ti-6Al-4V as well as Al6061 [46].

The following is an outline of the procedure for fuzzy TOPSIS:

Step 1: It is necessary to assign ratings not only to the conditions but also to the possibilities.

In the initial stages, it was operated with the presumption that the group responsible for making decisions was composed of K members. The fuzzy score of the Kth selection maker on replacement A_i regarding condition C_j is specified as $\tilde{x}_{ij}^{k} = \left(a_{ij}^{k}, b_{ij}^{k}, c_{ij}^{k}\right)$ and the weight of the criterion C_j is represented by the expression $\widetilde{w}_j^{k} = \left(w_{j1}^{k}, b_{j2}^{k}, c_{j3}^{k}\right)$.

Step 2: Evaluate the collected fuzzy reviews for the several choices that are accessible in addition to the consolidated weights on each criterion.

The following is the formula for calculating the weighted mean fuzzy score of the i^{th} choice concerning the j^{th} criteria $\tilde{x}_{ij} = \left(a_{ij}, b_{ij,}c_{ij}\right)$.

$$a_{ij} = min\,k\left\{a_{ij}^{k}\right\}, b_{ij} = \frac{1}{K}\sum_{k=1}^{k} \square\, b_{ij}^{k}, c_{ij} = max\,k\left\{c_{ij}^{k}\right\}. \quad (1)$$

Step 3: Calculate the outcomes with the help of the fuzzy decision matrix.
Step 4: Create the weighted normalization fuzzy determination matrix by carrying out the necessary calculations.
Step 5Determine the fuzzy positive optimum option and the fuzzy negative optimum option by doing the appropriate computations for each.
Step 6: Determine the distance from the FPIS and FNIS that separates each alternative.
Step 7: Calculate the CC_i similarity coefficient for each available alternative. To calculate the closeness coefficient CC_i for each possible alternative A_i, use the following formula:

$$CC_m = \frac{d_m^-}{d_m^- + d_m^*} \quad (2)$$

Step 8: Place each of the options in order. The alternative that offers the most potential benefits is the one that has the highest proximity coefficient [47].

E. Integrating GRA – in TOPSIS for multi-response optimization

The conventional TOPSIS technique is believed to have a few drawbacks, the most notable of which are its tendency to reverse rankings and its incapacity to take into account the relative significance of the distance between two reference points. The shortcomings of TOPSIS can be remedied by substituting the grey relational coefficient (GRC) of GRA for the definition of geometric distance. The hybrid GRA-TOPSIS model deviates from the traditional TOPSIS model in that it uses the grey relational coefficient rather than the geometric distance. The following is a rundown of the procedures required in using the hybrid GRA-TOPSIS method:
Step 1: Establishment of a decision matrix consisting of n replies and m possibilities.
Step 2: Compute the normalized version of the decision matrix, If the weight of each response is w_j, the computation of the weighted normalized decision matrix, V, looks like this: $[v_{ij}]$
where:

$$v_{ij} = w_j r_{ij}, Given\ \sum_{j=1}^{n} \square\, w_j = 1 \quad (3)$$

Step 3: Obtaining both the positive ideal (which represents the best) and the negative ideal (which represents the worst) responses:

$$V^{+/-} = \left\{\left(\sum_{i}^{max} \square\, v_{ij} | j \in J\right), \left(\sum_{i}^{min} \square\, | j \int_{\square}^{\square} \square\, J | k = 1,2,\ldots,m\right)\right\} = v_1^{+/-}, v_2^{+/-} v_3^{+/-} \ldots., v_n^{+/-} \quad (4)$$

Step 4: Calculating grey relational ratings involves finding the mean value of GRC.

$$GRC_{ij}^{-} = \frac{\Delta min_j + \varepsilon\Delta max}{\left(v_j^{+/-} - v_{ij}\right) + \varepsilon\Delta max} \quad (5)$$

Step 5: Position the potential options in descending order based on the value of Pi [48].

F. Surface roughness (SR)

The term "surface roughness" refers to the method of modifying the surface of the metal, which includes eliminating, restructuring, and adding components to the surface. Because of the irregularities in the surface, this could generate locations where corrosion or cracks first start. Utilizing a handheld SR tester, specifically the Mitutoyo Surfest SJ-2O1P, the values of SR can be determined and estimated [49].

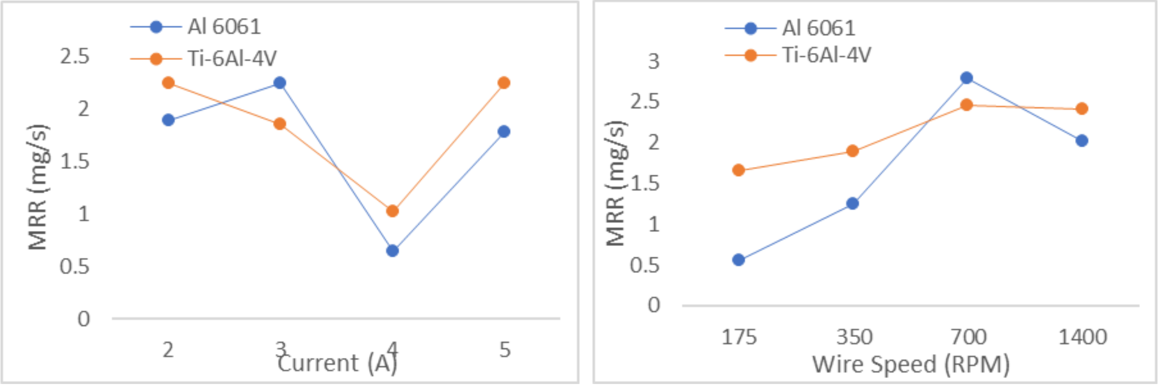
G. Estimation of MRR

The MRR is computed by taking the difference in weight between the workpiece before and after the procedure, as well as the combination of the time and the density of the substrate, into account. Equation (6) has been utilized for this particular research to determine the rate of material removal [50].

$$MRR = \frac{wt.\ before\ machining - wt.\ after\ machining}{time \times density} \quad (6)$$

IV. RESULTS AND DISCUSSION

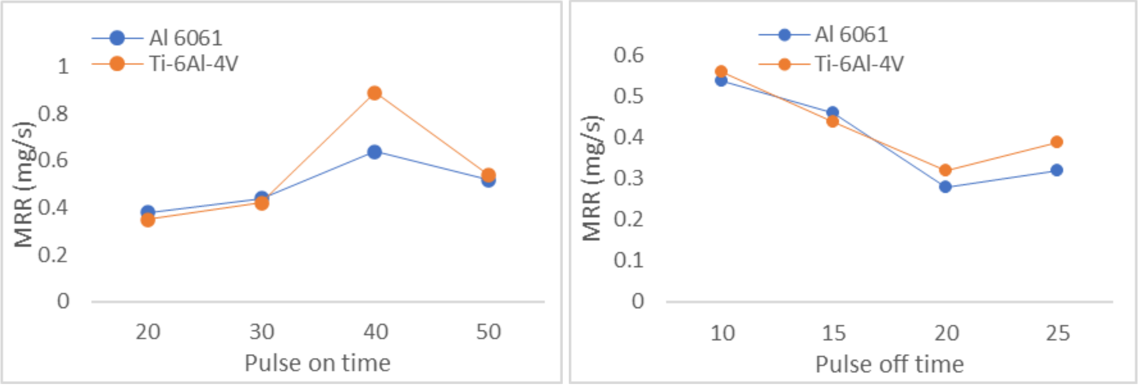
In this section the results that are obtained after the implementation is discussed in detail. Figure 3 (a) shows the effect of current on MRR for both the Al6061 and Ti-6Al-4V. It is observed that in the case of Al6061 the highest MRR rate is 2.25 achieved at 3 A current and the lowest MRR rate is 0.64 achieved at 4 Ampere current. On the other hand, for Ti-6Al-4V the highest MRR rate is achieved at 5 Ampere current i.e., 2.25 and the lowest MRR rate is achieved at 4 Ampere current i.e., 1.02. Figure 3 (b) shows the effect of wire speed on MRR for both the Al6061 and Ti-6Al-4V. It is observed that in the case of Al6061, the highest MRR rate is 2.78 achieved at 700 RPM and the lowest MRR rate is 0.56 achieved at 175 RPM. On the other hand, for Ti-6Al-4V the highest MRR rate is achieved at 700 i.e., 2.46 and the lowest MRR rate is achieved at 175 RPM i.e., 1.65.



(a) (b)

Figure 3 (a) Effect of current on MRR and Figure 3 (b) Effect of wire speed on MRR

Figure 4 (a) and (b) show the effect of pulse on time and pulse off time respectively on MRR for Al6061 and Ti-6Al-4V. From figure 4 (a) it is observed that for both the material as the pulse on time increases from 20 to 40, the MRR rate is also increased. This suggests that longer spark durations i.e., TON release more spark energy during each spark cycle, which causes bigger crater-sized material to melt. On the other hand, the MRR decreased when the TON exceeded 40 µs. This could result from the molten pool surrounding the craters recasting as a result of the longer operation time and lower spark frequency. It's interesting to note that, for both materials, increasing the TOFF duration from 10 µs to 25 µs led to a consistent decline in MRR, as Figure 4b illustrates. The duration during which sparking does not occur is known as the TOFF. As a result, lengthening the pulse length lengthens the cycle duration and decreases spark frequency. As a result, when the TOFF increased, the MRR decreased.



(a) (b)

Figure 4 (a) Effect of pulse on time on MRR Figure 4 (b) Effect of pulse off time on MRR

Figure 5 illustrates how voltage affects MRR for both Ti-6Al-4V and Al6061. There is a clear correlation between voltage and MRR. When the voltage in the spark gap increases from 80 V to 90 V, the MRR increases as well. Since the spark energy ($E = V \times I \times T\_on$) depends on the voltage, current, and TON. As a result, the increased voltage caused a larger volume of material to melt and evaporate, raising the MRR.

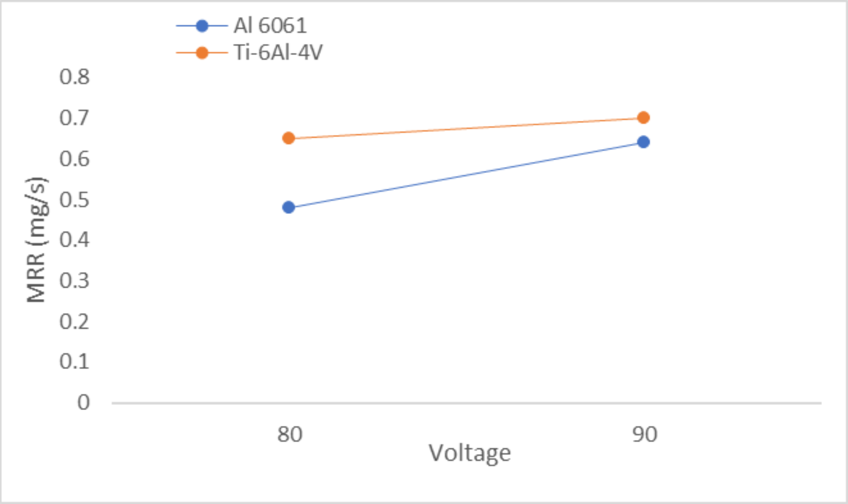
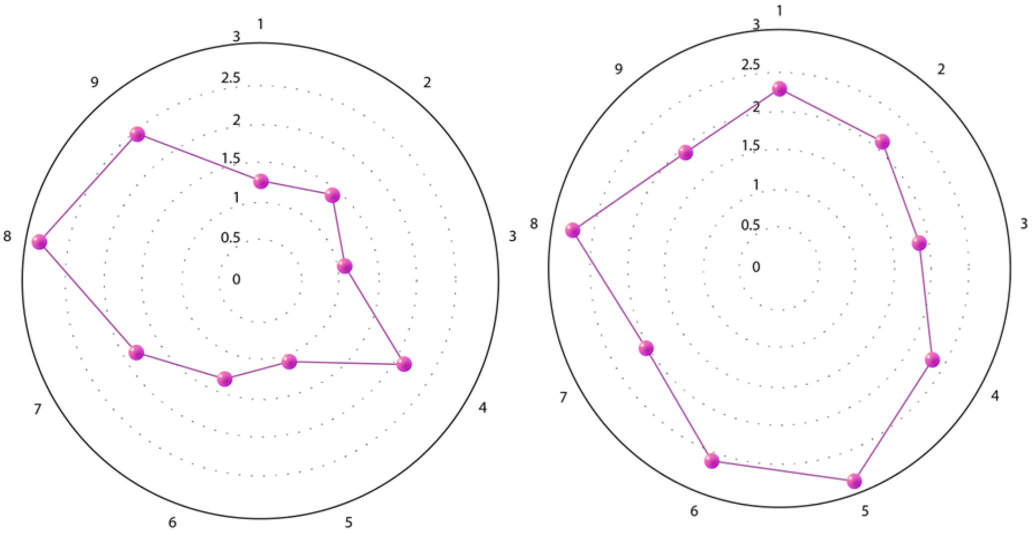


Figure 5 Effect of Voltage on MRR

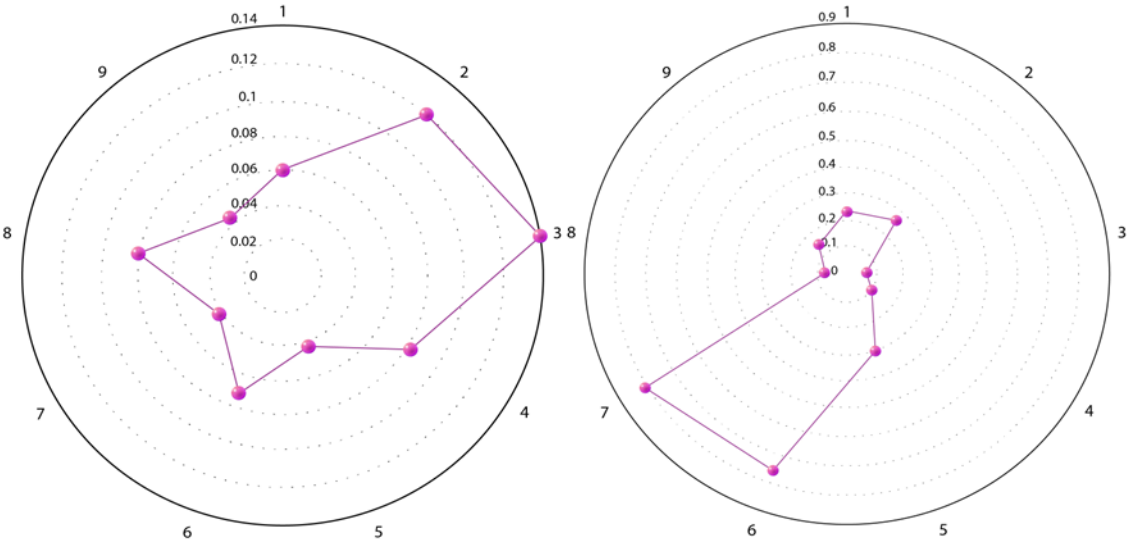
Figure 6 (a) and figure 6 (b) show the SR of Al6061 and Ti-6Al-4V respectively at various trials performed. The TON, TOFF, and wire tension had a significant influence on the SR value, but the other parameters were identical for both wire-EDM processing conditions. From Figure 6 (a) it is observed that the highest SR for Al6061 is 2.8 at trial no. 8 and the lowest SR value is 1.01 at trial no. 3. On the other hand, from Figure 6 (b) it is observed that the highest SR for Ti-6Al-4V is 2.9 at trial no. 5 and lowest SR values is 1.9 at trial 9.



(a) (b)

Figure 6 (a) SR of Al6061 and figure (b) SR of Ti-6Al-4V

Similarly, Figure 7 (a) and Figure 7 (b) show the DD of Al6061 and Ti-6Al-4V respectively at various trials performed. It is observed that for Al6061 the highest DD is 0.14 at trial no. 3 and the lowest DD value is 0.04 at trial no. 7. On the other hand, for Ti-6Al-4V it is observed that the highest DD is 0.8 at trial no. 7 and the lowest DD value is 0.08 at trial 8.



(a) (b)

Figure 7 (a) DD of Al6061 and figure (b) DD of Ti-6Al-4V

V. CONCLUSION AND FUTURE SCOPE

The current research investigated the Ti-6Al-4V and Al6061 material for parametric Optimization of the WEDM process by integrating GRA in TOPSIS as multi-response optimization. This investigation focused on five WEDM input process parameters, including voltage, wire speed, max current, TOFF, and TON. The impact of these processing factors on DD, SR, and MRR was the primary focus of the investigation. Ultimately, this study has concluded the following findings:

- The ideal parameters for machining AI6061 are voltage of 80V, wire speed of 700 RPM, TON of 20 µs, TOFF of 15 µs, and maximum current of 2 A.
- The ideal parameters for Ti-6Al-4V machining are 40 µs of TON, maximum current of 4 A, 25 µs of TOFF, 1400 RPM wire speed, and 80V of voltage.
- The optimal values for Al6061 are a roughness value of 1.01 Ra and a DD of 0.04. The output characteristics can be determined as the most unfavorable when the SR is 2.8 Ra, and the DD is 0.14.
- The optimal values for Ti-6Al-4V are a roughness value of 1.9 Ra and a DD value of 0.08. Similarly, the SR of 2.9 Ra and DD of 0.8 can be determined as the most unfavorable values for output characteristics.
- For Al6061, the maximum MRR rate is 2.23 at 3 A current and the lowest is 0.64 at 4 A current. In contrast, Ti-6Al-4V has a maximum MRR rate is 2.25 at 5 Ampere current, and the lowest rate is 1.02 at 4 Ampere.
- The MRR rates for Al6061 exhibit a maximum of 2.78 at 700 RPM and a minimum of 0.56 at 175 RPM. Conversely, with Ti-6Al-4V, the lowest MRR rate is 1.65 at 175 RPM, and the maximum MRR rate is 2.46 at 700.

In the future, GRA-TOPSIS can be further integrated with other optimization approaches, such as genetic algorithms, particle swarm optimization, or machine learning algorithms. Hybrid methodologies can provide improved optimization abilities, particularly in intricate and non-linear machining procedures.

REFERENCES

[1] Slătineanu, Laurenţiu, Oana Dodun, Margareta Coteaţă, Gheorghe Nagîţ, Irina Beşliu Băncescu, and Adelina Hriţuc. "Wire electrical discharge machining—A review." Machines 8, no. 4 (2020): 69.

[2] Das, Partha Protim, Sunny Diyaley, Shankar Chakraborty, and Ranjan Kumar Ghadai. "Multi-objective optimization of wire electro discharge machining (WEDM) process parameters using the grey-fuzzy approach." Periodica Polytechnica Mechanical Engineering 63, no. 1 (2019): 16-25.

[3] Chaudhari, Rakesh, Jay J. Vora, Vivek Patel, L. N. López de Lacalle, and D. M. Parikh. "Surface analysis of wire-electrical-discharge-machining-processed shape-memory alloys." Materials 13, no. 3 (2020): 530.

[4] Bisaria, Himanshu, and Pragya Shandilya. "Experimental investigation on wire electric discharge machining (WEDM) of Nimonic C-263 superalloy." Materials and Manufacturing Processes 34, no. 1 (2019): 83-92.

[5] Ablyaz, Timur Rizovich, Evgeny Sergeevich Shlykov, Karim Ravilevich Muratov, Sarabjeet Singh Sidhu, Dmitry Mikhailovich, and Khairulin Vadim Takhirovich. "Study of Wire-Cut Electro-Discharge Machining of Heat-Resistant Nickel Alloys." Materials 16, no. 20 (2023): 6743.

[6] Ulas, Mustafa, Osman Aydur, Turan Gurgenc, and Cihan Ozel. "Surface roughness prediction of machined aluminium alloy with wire electrical discharge machining by different machine learning algorithms." Journal of Materials Research and Technology 9, no. 6 (2020): 12512-12524.

[7] Ishfaq, Kashif, Muhammad Umar Farooq, and Catalin I. Pruncu. "Reducing the geometrical machining errors incurred during die repair and maintenance through electric discharge machining (EDM)." The International Journal of Advanced Manufacturing Technology 117, no. 9-10 (2021): 3153-3168.

[8] Prakash, Ved, P. Kumar, P. K. Singh, M. Hussain, A. K. Das, and S. Chattopadhyaya. "Micro-electrical discharge machining of difficult-to-machine materials: a review." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 233, no. 2 (2019): 339-370.

[9] Paturi, Uma Maheshwera Reddy, Suryapavan Cheruku, Venkat Phani Kumar Pasunuri, Sriteja Salike, N. S. Reddy, and Srija Cheruku. "Machine learning and statistical approach in modeling and optimization of surface roughness in wire electrical discharge machining." Machine Learning with Applications 6 (2021): 100099.

[10] Zaman, Uzair Khaleeq uz, Usman Ahmed Khan, Shahid Aziz, Aamer Ahmed Baqai, Sajid Ullah Butt, Danish Hussain, Ali Siadat, and Dong Won Jung. "Optimization of Wire Electric Discharge Machining (WEDM) Process Parameters for AISI 1045 Medium Carbon Steel Using Taguchi Design of Experiments." Materials 15, no. 21 (2022): 7846.

[11] Perumal, A., C. Kailasanathan, Balasubramaniam Stalin, S. Suresh Kumar, P. R. Rajkumar, T. Gangadharan, G. Venkatesan, N. Nagaprasad, V. Dhinakaran, and Ramaswamy Krishnaraj. "Multiresponse optimization of wire electrical discharge machining parameters for Ti-6Al-2Sn-4Zr-2Mo (α-β) alloy using taguchi-grey relational approach." Advances in Materials Science and Engineering 2022 (2022): 1-13.

[12] Murali, G., M. Murugan, K. Arunkumar, P. V. Elumalai, D. Mohanraj, and S. Prabhakar. "Investigation and Process Parameter Optimization on Wire Electric Discharge Machining of Aluminium 6082 Alloy." Advances in Materials Science and Engineering 2022 (2022).

[13] Priyadarshini, Manisha, Chandan Kumar Biswas, and Ajit Behera. "Machining of sub-cooled low carbon tool steel by wire-EDM." Materials and Manufacturing Processes 34, no. 12 (2019): 1316-1325.

[14] Binoj, J. S., N. Manikandan, P. Thejasree, K. C. Varaprasad, N. Prem Sai, and M. Manideep. "Machinability studies on wire electrical discharge machining of Nickel alloys using multiple regression analysis." Materials Today: Proceedings 39 (2021): 155-159.

[15] Singh, Thakur, Pawan Kumar, Jatinder Kumar, and Joy Prakash Misra. "Modeling of electric discharge wire cut of aviation grade alloy using fuzzy technique." Journal of Advanced Manufacturing Systems 21, no. 01 (2022): 255-274.

[16] Mostafapor, Amir, and Hossein Vahedi. "Wire electrical discharge machining of AZ91 magnesium alloy; investigation of effect of process input parameters on performance characteristics." Engineering Research Express 1, no. 1 (2019): 015005.

[17] Gowthaman, P. S., J. Gowthaman, and N. J. M. T. P. Nagasundaram. "A study of machining characteristics of AISI 4340 alloy steel by wire electrical discharge machining process." Materials Today: Proceedings 27 (2020): 565-570.

[18] Lalwani, Vishal, Priyaranjan Sharma, Catalin Iulian Pruncu, and Deepak Rajendra Unune. "Response surface methodology and artificial neural network-based models for predicting performance of wire electrical discharge machining of inconel 718 alloy." Journal of Manufacturing and Materials Processing 4, no. 2 (2020): 44.

[19] Fuse, Kishan, Arrown Dalsaniya, Dhananj Modi, Jay Vora, Danil Yurievich Pimenov, Khaled Giasin, Parth Prajapati, Rakesh Chaudhari, and Szymon Wojciechowski. "Integration of fuzzy AHP and fuzzy TOPSIS methods for wire electric discharge machining of titanium (Ti6Al4V) alloy using RSM." Materials 14, no. 23 (2021): 7408.

[20] Dwaipayan, De, Nandi Titas, and Bandyopadhyay Asish. "Parametric study for wire cut electrical discharge machining of sintered titanium." Strojnícky časopis-Journal of Mechanical Engineering 69, no. 1 (2019): 17-38.

[21] Gupta, Vivudh, Balbir Singh, and R. K. Mishra. "Machining of titanium and titanium alloys by electric discharge machining process: a review." International Journal of Machining and Machinability of Materials 22, no. 2 (2020): 99-121.

[22] Chaudhari, Rakesh, Jay J. Vora, Vivek Patel, L. N. López de Lacalle, and D. M. Parikh. "Surface analysis of wire-electrical-discharge-machining-processed shape-memory alloys." Materials 13, no. 3 (2020): 530.

[23] Gupta, Nitin Kumar, Nalin Somani, Chander Prakash, Ranjit Singh, Arminder Singh Walia, Sunpreet Singh, and Catalin Iulian Pruncu. "Revealing the WEDM process parameters for the machining of pure and heat-treated titanium (Ti-6Al-4V) alloy." Materials 14, no. 9 (2021): 2292.

[24] Pramanik, A., A. K. Basak, and C. Prakash. "Understanding the wire electrical discharge machining of Ti6Al4V alloy." Heliyon 5, no. 4 (2019).

[25] Dwaipayan, De, Nandi Titas, and Bandyopadhyay Asish. "Parametric study for wire cut electrical discharge machining of sintered titanium." Strojnícky časopis-Journal of Mechanical Engineering 69, no. 1 (2019): 17-38.

[26] Sivaprakasam, P., A. Kirubel, G. Elias, P. Maheandera Prabu, and P. Balasubramani. "Mathematical modeling and analysis of wear behavior of AlTiN coating on titanium alloy (Ti-6Al-4V)." Advances in Materials Science and Engineering 2021 (2021): 1-9.

[27] Safdarian, Rasoul. "Forming limit diagram prediction of 6061 aluminum by GTN damage model." Mechanics & Industry 19, no. 2 (2018): 202.

[28] Singh, Vijender, Kamal Kumar, and Puneet Katyal. "Experimental investigation on surface integrity and wear behavior of Ti-6Al-7Nb alloy under rough and trim cut modes of wire electrical discharge machining." Journal of Materials Engineering and Performance 30 (2021): 66-76.

[29] Paulson, Dheeraj Mathew, Mohd Saif, and Mohd Zishan. "Optimization of wire-EDM process of titanium alloy-Grade 5 using Taguchi's method and grey relational analysis." Materials Today: Proceedings 72 (2023): 144-153.

[30] Jebarose Juliyana, Sunder, Jayavelu Udaya Prakash, Charles Sarala Rubi, Sachin Salunkhe, Sharad Ramdas Gawade, Emad S. Abouel Nasr, and Ali K. Kamrani. "Optimization of Wire EDM Process Parameters for Machining Hybrid Composites Using Grey Relational Analysis." Crystals 13, no. 11 (2023): 1549.

[31] Adedeji, Wasiu Oyediran, Ebun Fasina, Mofoluwaso Kehinde Adeniran, K. A. Adedeji, J. Rajan, S. A. Oke, and E. O. Oyetunji. "Optimization of the wire electric discharge machining process of nitinol-60 shape memory alloy using taguchi-pareto design of experiments, grey-wolf analysis, and desirability function analysis." Indonesian Journal of Industrial Engineering & Management 4, no. 1 (2023): 28-50.

[32] Arya, Rashmi, and Hari Singh. "Optimization of Wire-cut EDM process parameters using TLBO algorithm." Engineering Research Express 4, no. 3 (2022): 035051.

[33] Kumar, Jatinder, Shubham Sharma, Jujhar Singh, Sunpreet Singh, and Gurminder Singh. "Optimization of Wire-EDM Process Parameters for Al-Mg-0.6 Si-0.35 Fe/15% RHA/5% Cu Hybrid Metal Matrix Composite Using TOPSIS: Processing and Characterizations." Journal of Manufacturing and Materials Processing 6, no. 6 (2022): 150.

[34] Doreswamy, Deepak, D. Sai Shreyas, Subraya Krishna Bhat, and Rajath N. Rao. "Optimization of material removal rate and surface characterization of wire electric discharge machined Ti-6Al-4V alloy by response surface method." Manufacturing Review 9 (2022): 15.

[35] Van Riel, Thomas, Jun Qian, and Bert Lauwers. "Exploratory study of wire based ECM finishing of 316L stainless steel, implemented within a hybrid wire EDM-ECM platform." Procedia CIRP 113 (2022): 465-470.

[36] Kumar, Ajay, Vishal Jagota, Rashed Qayoom Shawl, Vishal Sharma, Kumar Sargam, Mohammad Shabaz, Mohd Tanveer Khan, Basharat Rabani, and Smiley Gandhi. "Wire EDM process parameter optimization for D2 steel." Materials Today: Proceedings 37 (2021): 2478-2482.

[37] Ramaswamy, Arunbharathi, Ashoka Varthanan Perumal, Jayasuryaa Jagadeesan, and Harsha Vardhan Nagarajan. "Optimization of WEDM process parameters for D3 die steel using RSM." Materials Today: Proceedings 37 (2021): 2063-2069.

[38] Phate, Mangesh R., Shraddha B. Toney, and Vikas R. Phate. "Multi-parametric optimization of WEDM using artificial neural network (ANN)-based PCA for Al/SiCp MMC." Journal of The Institution of Engineers (India): Series C 102, no. 1 (2021): 169-181.

[39] Subburaj, Arulselvan, Ravindran Durairaj, Arul Marcel Moshi Antony Joseph Decruz, and Vignesh Kumar Dharmaraj. "Process-parameter optimization of WEDM with inconel 825 alloy using GRA." Materials and Technology 55, no. 2 (2021): 219-229.

[40] Alduroobi, Ahmed AA, Alaa M. Ubaid, Maan Aabid Tawfiq, and Rasha R. Elias. "Wire EDM process optimization for machining AISI 1045 steel by use of Taguchi method, artificial neural network and analysis of variances." International Journal of System Assurance Engineering and Management 11 (2020): 1314-1338.

[41] Soundararajan, R., A. Ramesh, K. Ponappa, S. Sivasankaran, and D. Arvind. "Optimization of WEDM process parameters by RSM in machining of stir cum squeeze cast A413–B 4 C composites." SN Applied Sciences 2 (2020): 1-21.

[42] Majumder, Himadri, Srimant Kumar Mishra, Anil R. Sahu, Anil Laxmanrao Bavche, Mahadev Valekar, and Bijaya Kumar Padaseti. "Application of MOORA to optimize WEDM process parameters: a multi-criteria decision making approach." In ICRRM 2019–System Reliability, Quality Control, Safety, Maintenance and Management: Applications to Civil, Mechanical and Chemical Engineering, pp. 73-78. Springer Singapore, 2020.

[43] Thangaraj, Muthuramalingam, Ramamurthy Annamalai, Khaja Moiduddin, Mohammed Alkindi, Sundar Ramalingam, and Osama Alghamdi. "Enhancing the surface quality of micro titanium alloy specimen in WEDM process by adopting TGRA-based optimization." Materials 13, no. 6 (2020): 1440.

[44] Wasif, Muhammad, Syed A. Iqbal, Anis Fatima, Saima Yaqoob, and Muhammad Tufail. "Experimental investigation for the effects of wire EDM process parameters over the tapered cross-sectional workpieces of titanium alloys (Ti6Al-4V)." Mechanical Sciences 11, no. 1 (2020): 221-232.

[45] Saif, Mohd, and Satyam Tiwari. "Investigation towards surface roughness & material removal rate in Wire-EDM of aluminium alloy 6061 and 5083 using Taguchi method." Materials Today: Proceedings 47 (2021): 1040-1047.

[46] Kumar, G. Venkata Ajay, and K. L. Narasimhamu. "Multi-objective optimization in WEDM of Inconel 750 alloy: application of TOPSIS embedded grey wolf optimizer." In Advanced Engineering Optimization Through Intelligent Techniques: Select Proceedings of AEOTIT 2018, pp. 231-240. Springer Singapore, 2020.

[47] Lei, Gang, Heqing Song, and Dragan Rodriguez. "Power generation cost minimization of the grid-connected hybrid renewable energy system through optimal sizing using the modified seagull optimization technique." Energy Reports 6 (2020): 3365-3376.

[48] Abhilash, P. M., and D. Chakradhar. "Multi-response optimization of wire EDM of Inconel 718 using a hybrid entropy weighted GRA-TOPSIS method." Process Integration and Optimization for Sustainability (2022): 1-12.

[49] SAIF, MOHD, and Ritik Kumar Rawat. "Investigation of aluminum alloy 6061 in Wire-EDM regarding surface roughness and material removal rate by adopting optimization techniques." Journal of Mechanical Engineering and Sciences (2023): 9410-9420.

[50] Doreswamy, Deepak, Anupkumar M. Bongale, Marcin Piekarski, Arunkumar Bongale, Satish Kumar, Danil Yurievich Pimenov, Khaled Giasin, and Krzysztof Nadolny. "Optimization and modeling of material removal rate in wire-EDM of silicon particle reinforced Al6061 composite." Materials 14, no. 21 (2021): 6420.