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OPTIMIZATION OF EDM FOR AA6061/10%AL_2O_3 AMMC USING TAGUCHI SCHEMES AND ANALYTICAL HIERARCHY PROCESS FOR WEIGHT DETERMINATION

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ABSTRACT

Previously, some authors proposed the innovative Taguchi–ABC and Taguchi–Pareto optimization tools to concurrently optimize and prioritize processes. In this paper, the models were used to optimize the electrical discharge machining (EDM) process parameters of AA6061/10%Al2O3 AMMC, validated with published data. Besides, the analytical hierarchy process (AHP) was used to determine the weight of factors. The Taguchi–Pareto 80/20 method utilizes the smaller-the-better quality attribute and a complimentary effort of the analysis of variance. The Taguchi-ABC uses the classified A, B and C schemes to prioritize the parameters. The AHP ranks the system as sub-problems of the top-level objective hierarchy followed by lower-level sub-criteria and bottom level variables. The results show the decreasing order of factors (pulse-on-time > peak current > duty factor) for Taguchi analysis and Taguchi-Pareto. The later yielded the optimal parametric setting of A1B2C2, indicating peak current of 6 amps, pulse-on-time of zero and duty factor of 0.6. The Taguchi-ABC reduced to Taguchi AB (i.e. optimal parametric setting as A1 B2) whereby the C (duty factor) yielded lower delta value than B (pulse-on-time). The AHP offered a conflicting result with duty factor having the largest criteria weight and the order of the weights of the factors is duty factor > pulse-on-time > peak current. The consistency ratio was 0.07 > 0.1. The results would aid EDM process engineers to effectively manage the EDM process.

KEYWORDS

Optimization, EDM, Taguchi methods, prioritization, analytical hierarchy process.

1. INTRODUCTION

Currently, the electrical discharge machining (EDM) does not take in consideration parametric optimization in concurrence with prioritisation of factors and equal importance is given to the process factors (Dey et al., 2017; Gangil and Pradhan, 2017; Dey et al., 2018; Kandpal et al, 2018; Gudipudi et al., 2019; Kim et al., 2018; Zhang et al., 2019; Gore and Patil 2018). This opinion may yield redundant allocation of scarce EDM process resources and may sometimes deny legitimate factors of the needed resources despite the danger of system failure that threatens the EDM process (Siegel, 1965; Klocke et al., 2016). To tackle this concern, the current article proposes two frameworks involving the applications of Taguchi–Pareto and Taguchi–ABC as a framework, and the analytical hierarchy process (AHP) as a second framework. The first two models could concurrently optimize and prioritize factors (Ajibade et al., 2016; Nwafor et al., 2019). This is useful and will methodically advise the EDM process engineers on how the distribution of scarce EDM process resources should be made for efficiency and the most rewarding process output.

To ease such optimization, the Taguchi–Pareto and Taguchi-ABC utilize the L9 33 orthogonal array, signal-to-noise quotient and the criterion of smaller-the-better as well as the analysis of variance (ANOVA) (Ajibade et al., 2019b; Nwafor et al., 2019). The AHP ranks the system as smaller sub-problems of the top-level objective hierarchy followed by lower-level subcriteria and bottom level variables (Samvedi et al., 2012; Qattawi et al., 2013; Arunachalam et al., 2019). The Pareto and ABC components of the Taguchi-Pareto and Taguchi-ABC frameworks are anticipated to obtain characteristics that are employed for prioritization in the concurrent scheme of optimization and prioritization of these two frameworks and this will help to arrive at the eventual optimization results (Ajibade et al., 2016; Ajibade et al., 2019b). The new idea of this work is the unique joining of Taguchi and each of Pareto and ABC analysis to optimize and concurrently prioritize EDM process factors for the first time. The validation of the model was conducted using results of a previous study by Kandpal et al. (2017). The outcome of the study reveals that the proposed approaches of Taguchi–ABC can offer feasible results in EDM processes. Besides, an innovative method of AHP has been proposed for the first time in the ranking of the EDM process factors. The AHP was verified to produce feasible results for the literature data examined (Kandpal et al., 2017).

Furthermore, at present, despite the EDM process being saturated with various optimization studies, investigations on EDM of AA6061/10%Al2O3 are still at their infancy and no study has considered the concurrent optimization with the prioritization of factors (Kandpal et al., 2017; Kandpal et al., 2018). Furthermore, in any of the available studies, there is no report on the analytical hierarchy process to strengthen the objective analysis of factors in terms of optimization (Kandpal et al., 2017; Kandpal et al., 2018). Notwithstanding, there is an increasing gap in practice concerning the concurrent optimization and prioritization of EDM process factors. Currently, there is insufficient information on the relative importance of EDM process factors accessible to the EDM process engineer during budgetary and planning tasks (Klocke et al., 2016; Kandpal et al., 2017; Kandpal et al., 2018; Kim and Chu, 2018; Gudipudi et al., 2019). As no serious attention seems to be given to this problem and with the expanding population of users of EDM process, and the EDM of AA6061/10%Al2O3 AMMC in particular, this misguidance in the computation of optimal results are projected to worsen in the coming years (Kandpal et al., 2017). Thus, state of research on EDM process needs an intervention regarding optimization and prioritization of the EDM for AA6061/10%Al2O3 AMMC. Besides, there is an urgent requirement to tackle this poorly researched area to attain an immediate and lasting solution to impact on EDM process decision making (Kandpal et al., 2017).

2. LITERATURE REVIEW

Daily, the EDM process engineer is normally accountable to execute the G-code programming to operate the EDM machines and set up. To achieve this role, the EDM process engineer combines blueprints and process sheets to establish the accurate setting for components. Besides, the EDM process engineer conducts planned maintenance tasks such as machine cleaning and tool sharpening. In all, the EDM process engineer has dozens of activities and confrontations that insist on his/her attention. Along with these, the peak current, pulse-on-time and duty factors are three factors that insist on the EDM process engineer's attention that directly affect the output of the system as well as the ability of the process engineer to prioritise. These do not give the same importance during computations. So, this challenge needs to be solved using scientific tools and Taguchi-Pareto, and Taguchi-ABC methods have been developed to tackle the concurrent optimization and prioritization problem.

The Taguchi–Pareto and Taguchi–ABC methods have several significant concurrent optimization and prioritization values in the area of engineering practices, which have not been extensively validated scientifically (Nwafor et al., 2019; Ajibade et al., 2019b). For instance, using the Taguchi–Pareto and Taguchi–ABC methods could be a valuable prioritization opportunity to assist the EDM process as the prioritization of parameters will assist the process engineer to ascertain that the time, available resources and costs are properly expended and that the process engineer is focusing on the accurately important factors and the necessary attention is devoted to such factors. Reported use of Taguchi–Pareto and Taguchi–ABC methods has their potential to optimize the process parameters (Nwafor et al., 2019; Ajibade et al., 2019b). Ajibade et al. (2019b) employed the powerful characteristics of the analysis of variance (ANOVA) to detect factors that impose significant deviations from the target values in terms of variance to develop the 80/20 Pareto rule, which was integrated into Taguchi scheme. Apart, the ABC scheme in inventory analysis was brought into an argument to develop the Taguchi–ABC scheme. The study has not identified the electrical discharge machining process as an area for potential value-adding by the application of the newly developed Taguchi–Pareto and Taguchi–ABC. Furthermore, the widely used aluminium metal matrix composite of AA6061/10%Al_2O_3 has not been previously reported in the literature for the EDM process parametric optimization.

Nwafor et al. (2019) utilized Taguchi method, Taguchi-Pareto and Taguchi-ABC to optimize the parameters of a casting process for A356 alloy composite. The feasibility of applying the methods in a practical situation was confirmed by the authors. Ajibade et al. (2016) applied Taguchi-Pareto scheme to optimize the tapped density parameters of four agricultural wastes. It was confirmed that the model worked properly.

Next, Hussein et al. (2019) addressed the optimization of hardness of medium carbon steel through the employment of classical Taguchi's technique. By laying building blocks around the L18 orthogonal array, it was shown that the tempering temperature obtained at 100°C has the most significant impact on hardness characteristics of the studied steel. While the current paper and that paper shares a common framework of Taguchi scheme, it has not considered prioritization in the scheme of optimization in a concurrent manner, hence, there is a research gap regarding this in literature. Ajibade et al. (2019a) employed the Taguchi's framework to obtain the utmost results in a tribological experiment to obtain the behavior of newly fabricated composites in five options. Based on the parameters of load/speed, load/mass and time/speed, the options were computed in terms of optimal parameters as A1B2-3C3D1E4, A3B2C3D3E2 and A3B2C4D3E3. Nonetheless, no mention was made concerning prioritization of factors and Taguchi–Pareto as well as Taguchi–ABC was not used. But the gap still remains to be bridged till date. Ajibade et al. (2019b) championed the introduction of Taguchi–Pareto and Taguchi–ABC as useful tools to concurrently prioritize process parameters with inferences drawn from a water absorption system in composite development. Drawing parameters from the sample thickness, final and initial weights and the period of immersion of samples, it was clearly demonstrated that Taguchi–Pareto and Taguchi–ABC could be utilized as superiors to the conventional Taguchi scheme incorporating factor/levels, orthogonal arrays and signal-to-noise quotient as opposed to the additional tools of ANOVA and Pareto analysis (for Taguchi–Pareto) and ABC analysis (for Taguchi–ABC). Nonetheless, the application of this to other areas such as electrical discharge machining remains a gap to be filled.

This work aims to promote the use of Taguchi–Pareto and Taguchi–ABC in manufacturing. Thus, the following conclusions are derived from the literature review:

1) Only recently has there been an awakening involving the use of Taguchi–Pareto and Taguchi–ABC (Ajibade et al., 2019b) by the fusion aspect of at least two models, by combining Taguchi and Pareto analysis as well as Taguchi and ABC.
2) Some studies have been conducted on the application of Taguchi method to optimize aluminium matrix composites during the EDM machining.
3) There is need for studies to optimize and concurrently prioritize factors in the EDM research domain to machine AA6061/10%Al_2O_3 AMMC.

3. METHODOLOGY

Three process parameters (peak current, pulse-on-time and duty factor) with their values at three levels, extracted from Table 2 of Kandpal et al. (2017) were used. The L9 orthogonal array was selected using Minitab 16 software for experimental design of the process parameters and their levels. In Kandpal et al. (2017), drilled holes were cut by EDM and since shape may play a role in the surface roughness and electrode wear rate of EDM of AA6061/10%Al_2O_3 AMMC, the optimization effort here is directed towards making quality holes. Today, EDM drilling has appeared in hole-making at the minimum sizes, improving on earlier technology used on hard metals. The technology of EDM has advanced to integrate digital generators with software for more economical production and enhanced spark control.

3.1. Taguchi Method

The parametric design of Taguchi is used to obtain ideas proposed in this work for the optimization of EDM for AA6061/10%Al_2O_3 AMMC. Subsequently, the objective function utilized is as stated here (Ajibade et al, 2019b):

$$S/N = -10 * \log10(1/n * \sum y_i^2) \quad (1)$$

3.2. Taguchi-Pareto 80/20 method

Pareto analysis may impact on the EDM process where the major parameters of pulse-on-time, peak current and duty factor are contending for consideration. In this instance, the EDM process engineer assesses the advantages provided by each factor and then chooses the factor that dispenses the whole advantages that is convincingly near the utmost possible one. This employs the 80/20 rule founded on the principle that 20% of the factors contribute to 80% of the success of the EDM process. However, it is known that hybrid models combine the advantages of the component models. Thus, combining the Taguchi principle of cost reduction, product quality enhancement and vigorous optimization solutions will help to synergize the advantages of Pareto analysis and Taguchi method in a concurrent activity of optimization of process parameters and prioritization of important factors in the EDM process. Thus, Taguchi-Pareto model is beneficial for the EDM process and should be fully exploited for the most beneficial experience by the EDM process.

In Taguchi-Pareto 80/20 method, 20 % of the factor levels were found to correspond to 80% of the total cumulative percent which point to the fact that they are efficient to optimize over other factor levels. Therefore, other factors are not economical to optimize and are not considered for further investigation (Ajibade et al, 2019b). The equation below gives the objective function of the optimization as follows (Ajibade et al, 2019b):

$$S/N = -10 * \log 10(1/n * \sum P_{80/20} y_i^2) \quad (2)$$

where yi is the measured value of the smaller-the-better quality characteristic, n is the number of tests in every trial condition and S/N is the signal-to-noise ratio of the system.

According to Ajibade et al. (2019b), analysis of variances (ANOVA) is a mathematical method is used to evaluate the individual influence of the governable factors on the quality characteristic. The Taguchi method provides the details for selecting the optimal setting of parameters for the system and important information useful for further evaluation. With the use of the ANOVA, the overall variation from the mean S/N ratio is separated into individual parameters. The ANOVA result obtained after inputting the factors at different levels are shown in Table 1.

The following definitions may be helpful to understand the various factors in an electrical discharge machining system:

Peak current: It is described by some authors as the most essential parameter in the EDM process. It relates to the quantity of power used up in the discharge machining process (Kandpal et al., 2017).

Pulse-on-time: The pulse-on-time is also known as the pulse duration and shows the time gap from the discharge of electrons (spark) on the wire (electrode) and the workpiece. This happens as the breakdown voltage of the dielectric is attained, which produce ions. From this point, the spark produced leads to the workpiece material erosion (Kandpal et al., 2017).

Duty factor: The nomenclature, duty factor describes the proportion of the pulse duration to the total cycle time, and it is often stated to be the distance between the tool and the workpiece (gap provided by the servo mechanism) (Kandpal et al., 2017).

Table 1. ANOVA table.

Anova: Two-factor without replication				
Summary	Count	Sum	Average	Variance
A: Peak current (amps)	3	30	10	16
B: Pulse-on-time (μs)	3	375	125	4375
C: Duty factor	3	1.8	0.6	0.01

3.3. Taguchi-ABC method

The ABC classification has been used to rank data or observations based on their cumulative percentage of the sum total as shown in the last column of Table 2 (cumulative).

Table 2. Taguchi Pareto 80/20 rule.

S/N	S/N ratio (order)	Cumulative Value	% Cumulative
1	-41.2614	-41.2614	0.12577
2	-36.4877	-77.7491	0.23700
3	-36.4682	-114.2173	0.34816
4	-36.4464	-150.6637	0.45926
5	-36.4438	-187.1075	0.57035
6	-36.4407	-223.5482	0.68143
7	-36.4186	-259.9668	0.79244
8	-35.2767	-295.2435	0.89997
9	-32.8146	-328.0581	1.00000

Thus, the observations which have a cumulative percentage of 66.6 % to the total sum are designated as A. The observations which makes up the next 23.3 % are termed B, while the last set of observations which adds up 10.1 % are regarded as C. Applying this rule to the Taguchi method, the factor levels are ranked A, B and C. These new factor levels classified as A, B and C are grouped as factors for Taguchi optimization irrespective of initial factor groupings. Thus, the optimal results are not in terms of units but in terms of individual contributions to the quality characteristic. The objective function is modified as follows in Equation (3) (Ajibade et al., 2019b):

$$S/N = -10 * \log10(1/n * ABC\sum y_i^2) \quad (3)$$

3.4. Analytical Hierarchy Process

In the EDM process, the engineer focuses on three factors, namely, peak current, pulse-on-time and duty factors. But the engineer has the problem of inability to choose the most appropriate and consistent factors such that they are in considered affiliation with the goals of the EDM process. The engineer also has various groups of stakeholders that are pursuing an outcome for the process. However, these stakeholders may not concur to which factors are the most important. To worsen the situation, these stakeholders have their judgements and opinions about the factors, which may not be rational but biased. Besides, there is a limited set of resources to accompany the objective of the EDM process. Since it is known that the resource are never enough for the EDM process engineer to fulfill the system's objective, the prioritization of these factors is the solution to this problem and the use of analytical hierarchy process may satisfy this need. More so, the portfolio of the EDM process engineer is to produce high quality machined products, but this has to be achieved with the inputs of all the stakeholders in the EDM process industry. The AHP works on a set of criteria that are defined, evaluated and translated into weighted attributes. AHP is unique compared with other techniques in the manner that the weight of the criteria is judged. The AHP disintegrates this issue into smaller number of judgements.

For this study, three process parameters were considered for parametric optimization and must be of priority in the optimization and characterization of EDM of AA6061/10%Al2O3 AMMC among the following factors; peak current, pulse-on-time and duty factor. The complex problem is broken down into smaller sub-problems of top-level objective hierarchy, followed by lower-level sub-criteria and bottom-level variables (Fig. 1).

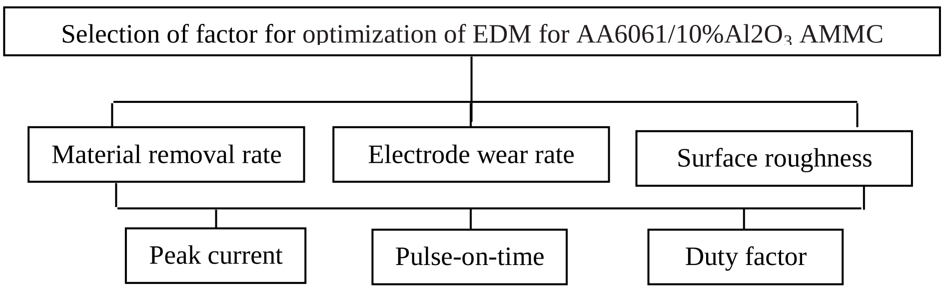

Fig. 1. Hierarchy of optimization of EDM for AA6061/10%Al2O3 AMMC.

4. RESULTS AND DISCUSSION

In the EDM process, there are often different kinds of aluminium alloys and ceramic materials that could be hybridized to serve the purpose of civil aviation and automobile sectors (Kandpal et al., 2017). Examples of aluminium alloys are Al6061, Al 8000, duralumin, Alnico, Alclad, birmabright and Al-Li. Examples of ceramic materials are glass, bricks, clay, Al_2O_3, and tiles. However, a usual material selection problem is to choose a combination of alloys and ceramic materials where the resulting hybrid is expected to possess outstanding mechanical, physical, thermal, and chemical properties. The tradeoff among these properties brings about the challenge of searching for a material with unique advantages but still with the economic benefit of being cheap. Thus, it is obligatory for process engineers to reflect on the various material substitutes using an understanding of their properties and characteristics, which can assist to gain understanding into the interrelated properties of aluminium alloys and ceramic materials and confine the necessary characteristics of a practical yet cheap material option. However, regarding their Poisson ratio, tensile strength, thermal expansion, yield strength, electrical resistivity, thermal conductivity, hardness, and the association between these materials, the hybridization of the aluminium alloys and ceramic materials may be more complex. Consequently, the combination of Al 6061 and Al_2O_3 would be an ultimate material combination to pursue in the context of EDM process and the machining of aluminium based composite materials.

In this section, the published data on the EDM process experiments, carried out by Kandpal et al. (2017) is shown in Table 3. Succeeding progress on the computation of results for the Taguchi-Pareto, Taguchi-ABC and the AHP models was attempted to observe the behavior of the parameters.

Table 3. Kandpal et al.'s (2017) experimental data on EDM process parameters.

	Level		
Parameter	1	2	3
A: Peak current (amps)	6	10	14
B: Pulse-on-time (μs)	75	100	200
C: Duty factor	0.5	0.6	0.7

4.1. Taguchi analysis

The process parameters are peak current, pulse-on-time and duty factor with their levels which are taken into account are shown in Table 1. Experimental trials were carried out using

Taguchi's L933 orthogonal array as shown in Table 4 (with 3 factors and 3 levels) which allows you to consider a selected subset of combinations of multiple factors at multiple levels for optimization of EDM for AA6061/10%Al_2O_3 AMMC as shown in Table 5.

Table 4. Taguchi L933 experimental design.

	A: Peak Current (amps)	B: Pulse-on-time (µs)	C: Duty factor	S/N ratio
1	6	75	0.5	-32.7579
2	6	100	0.6	-35.2446
3	6	200	0.7	-41.2533
4	10	75	0.6	-32.8068
5	10	100	0.7	-35.2722
6	10	200	0.5	-41.2603
7	14	75	0.7	-32.8791
8	14	100	0.5	-35.3132
9	14	200	0.6	-41.2707

Table 5. Taguchi S/N ratios response table.

Level	A: Peak current (amps)	B: Pulse-on-time (µs)	C: Duty factor
1	-36.4186	-32.8146	-36.4438
2	-36.4464	-35.2767	-36.4407
3	-36.4877	-41.2614	-36.4682
Delta	0.0691	8.4468	0.0276
Rank	2	1	3
	A1	B1	C2

4.2. Taguchi Pareto 80/20 analysis

The factor levels with significant variance are the 20% found to represent the 80% of total cumulative percentage which means that they are economical to optimality why the remaining are not. The number of factors level is then reduced to seven (7) as shown in Table 6. Table 7 shows the Taguchi-Pareto L933 experimental design for optimization of EDM for AA6061/10%Al_2O_3 AMMC.

In the Taguchi-Pareto 80/20 analysis, Table 8 shows that A1B2C2 is the optimal parameter setting (Peak current of 6 amps, Pulse-on-time of zero and Duty factor of 0.6) for optimization and characterization of EDM of AA6061/10%Al2O3 AMMC. The Taguchi-Pareto 80/20 analysis shows that when these factors are merged, they can give what is needed in the optimization of EDM for AA6061/10%Al_2O_3 AMMC due to their influence.

Table 6. Process parameters and levels for Taguchi Pareto 80/20 analysis.

Parameters	Level 1	Level 2	Level 3
A: Peak current (amps)	6	10	14
B: Pulse-on-time (µs)	-	-	200
C: Duty factor	0.5	0.6	0.7

Table 7. Taguchi-Pareto L933 experimental design.

	A: Peak Current (amps)	B: Pulse-on-time (µs)	C: Duty factor	S/N ratio
1	6	0	0.5	-10.821868
2	6	0	0.6	-10.835026
3	6	200	0.7	-41.253347
2	10	0	0.6	-15.244394
3	10	0	0.7	-15.250016
1	10	200	0.5	-41.260258
3	14	0	0.7	-18.162192
1	14	0	0.5	-18.156884
2	14	200	0.6	-41.270655

Table 8. Taguchi Pareto 80/20 S/N ratios response table.

Level	A: Peak Current (amps)	B: Pulse-on-time (µs)	C: Duty Factor
1	-20.9701	-14.7428	-23.4130
2	-23.9182	-11.0605	-22.4500
3	-25.8632	-41.2614	-24.8885
delta	4.8932	30.2009	2.4385
Rank	2	1	3
	A1	B2	C2

4.3. Taguchi-ABC method

The process parameters and levels were grouped into factor A, B and C using the ABC classification as shown in Table 9. Table 10 describes a special mix-design L933orthogonal array for experimental design. This formed an ideal parameter setting based on the individual influence of the factor levels regardless of their initial factor grouping. Table 11 shows a revised Taguchi-ABC S/N response.

Table 9. Process parameters and levels for Taguchi-ABC analysis.

	1	**2**	**3**
B: Pulse-on-time (µs)	75	100	200
C: Duty factor	0.5	0.6	0.7

In the Taguchi-ABC analysis, Table 11 shows that A1B2 is the optimal parameter setting (Pulse-on-time of 75 µs and Duty factor of 0.6) for Optimization and characterization of EDM of AA6061/10%Al_2O_3 AMMC. The Taguchi-ABC analysis shows that when these factors are merged can give what is needed in the optimization of EDM for AA6061/10%Al_2O_3 AMMC as a cause of their influence.

Table 10. Taguchi-ABC L933 experimental design.

S/No.	**B: Pulse-on-time (µs)**	**C: Duty Factor**	**S/N Ratio**
1	75.00	0.5	-31.480818
2	75.00	0.6	-31.480903
3	75.00	0.7	-31.481004
4	100.00	0.5	-33.979509
5	100.00	0.6	-33.979556
6	100.00	0.7	-33.979613
7	200.00	0.5	-40.00003
8	200.00	0.6	-40.00004
9	200.00	0.7	-40.000053

Table 11. Taguchi-ABC ratios response table

Level	**B: Pulse-on-time (µs)**	**C: Duty Factor**
1	-31.4809	-35.1535
2	-33.9796	-35.1535
3	-40.0000	-35.1536
delta	8.5191	0.0001
Rank	2	1
	A1	B2

4.4. Analytical Hierarchy process

Three different process parameters were considered in order to know the particular process factor to be prioritized for optimization of EDM for AA6061/10%Al_2O_3 AMMC. The result from the experiment is then analyzed to obtain the decision matrix as shown in Table 12.

Table 12. Decision matrix for the four factors.

	A: Peak current (amps)	B: Pulse-on-time (µs)	C: Duty factor
A: Peak current (amps)	1	0.33	0.2
B: Pulse-on-time (µs)	3	1	0.25
C: Duty factor	5	4	1
Total	9	5.33	1.45

The values in Table 12 were used to calculate the normalize values by dividing each of the values in the column by the sum of values of the factors for a particular column after which the normalized values are going to be used to form the normalized matrix. The criteria weight is then is then determined for all the four factors using the normalized matrix as shown in Table 13.

Criteria weight (peak current) = (0.1111 + 0.0625 + 0.1379)/3 = 0.1038

Criteria weight (pulse-on-time) = 0.2311

Criteria weight (duty factor) = 0.6651

Table 13. Normalize matrix with the criteria weight for the four factors.

	A: Peak current (amps)	B: Pulse-on-time (µs)	C: Duty factor	Criteria weight
A: Peak current (amps)	0.1111	0.0625	0.1379	0.1038
B: Pulse-on-time (µs)	0.3333	0.1875	0.1724	0.2311
C: Duty factor	0.5555	0.75	0.6897	0.6651

The weight sum value for each of the four factors in consideration were obtained as shown in Table 14.

Table 14. Weight sum value for each of the four factors.

	A: Peak current (amps)	B: Pulse-on-time (µs)	C: Duty Factor	Weight sum value
A: Peak current (amps)	0.1038	0.0763	0.1330	0.3131
B: Pulse-on-time	0.3115	0.2311	0.1663	0.7088
C: Duty factor	0.5192	0.9243	0.6651	2.1085

After the weight sum values have been calculated, the next thing to do is to check the factor matrix for consistency. Consistency in the matrix is important, because it shows how precise the result of the process will be.

$$\text{Consistency index CI} = (\lambda_{max} - n)/n-1 \qquad (4)$$

where λ_{max} = Ave[(weight sum value) / (criteria weight)]

n = number of factors considering

Table 15 is the information concerning the ratio of weight sum value to criteria weight

Table 15. Ratio of weight sum value to criteria weight.

	Weight sum Value (WSV)	**Criteria weight (CW)**	**WSV/CW**
A: Peak current (amps)	0.3131	0.1038	3.0154
B: Pulse-on-time (µs)	0.7088	0.2311	3.0677
C: Duty factor	2.1085	0.6651	3.1704
			λmax = 3.0845

λmax = (3.0154 + 3.0677 + 3.1704)/3 = 3.0845

Consistency index = (λmax - n)/(n - 1) = (3.0845 - 3)/(3 - 1) = 0.0423

4.5. Consistency ratio

Consistency Ratio is a comparison between Consistency Index and Random Index. The in consistency is acceptable if the value of Consistency Ratio is lesser or equal to 01, but if the Consistency Ratio is greater than 0.1, the values of process parameters from the experiment need to be revised. From the Table 16, random index (RI) of 0.58 is used because there are only three process parameters.

Table 16. Random consistency index (Triantaphyllou and Mann, 1995).

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Consistency ratio = Consistency index / Random index

From the random index table, when n = 3, random index = 0.58

Therefore consistency ratio = (0.0423) / (0.58) = 0.07 < 0.1

The matrix is Consistent because the consistency ratio is less than 0.1

Taking into account the results of the criteria weight as well as those of the weight sum value analysis, the final factor to be taken as priority using the AHP method for the optimization of EDM for AA6061/10%Al2O3 AMMC is the duty factor. Therefore, concerning the main objective of the model (AHP), duty factor was selected as the most appropriate factor to prioritize.

4.6. Comparison of the current paper with literature data

In this section, analysis has been done to compare results of the current study with those obtained by the experiment, Taguchi's method and utility concept's values of Kandpal et al. (2017). It also compared the current outcomes with the method of Chakraborthy and Das (2019) that employs the fuzzy logic method. Table 17 shows the results of the various methods compared to reveal similarities and dissimilarities.

Table 17. Comparison of current study with literature results

	Current study			Chakraborty and Das (2019)		Kandpal et al. (2017)		
Method→ Input parameters↓	Taguchi-Pareto	Taguchi-ABC	AHP (Criteria weights)	Fuzzy logic (minimum value)	Fuzzy logic (maximum value)	Taguchi method	Utility concept	Experimental
Peak current (amps)	6	-	0.1038	6	14	Ranges from 6 to 14	6	Ranges from 6 to 14
Pulse-on-time (μs)	0	75	0.2311	75	200	75	Ranges from 75 to 200	Ranges from 75 to 200
Duty factor	0.6	0.6	0.6651	0.5	0.7	.5	.4	Ranges from .5 to .7

Based on the analysis carried out in this paper and the other authors whose results are compared with the present article, the following conclusions can be drawn:

1. There is agreement of results of Taguchi-Pareto (peak current) with the experimental values, Taguchi scheme's results and utility concept's values of Kandpal et al. (2017).
2. Taguchi-Pareto could not predict well the pulse-on-time value but concurrence occurs between Chakraborty and Das' (2019) results, the experimental values, Taguchi scheme's results and utility concept's values of Kandpal et al. (2017). The inability of the current Taguchi-Pareto's model to predict the experimental values was due to the effect of prioritization on the outcome, which changes the value to zero.
3. The duty factor of Taguchi-Pareto is slightly higher, but can be judged to predict and concur with other models such as the fuzzy logic model such as the fuzzy logic model of

Chakraborty and Das (2019), the experimental values, Taguchi model's values and utility concept's values of Kandpal et al. (2017). The 20% excess in value is due to the influence of prioritization that Taguchi-Pareto has taken care of.

4. The Taguchi-ABC could not predict the peak current as it considers it unnecessary when prioritizing factors.
5. The Taguchi-ABC (pulse-on-time) effectively predicted the same values as given by Chakraborty and Das (2019), the experimental values, Taguchi model's values and utility concept's values of Kandpal et al. (2017).
6. The Taguchi-ABC (duty factors) has a 20% higher value than Chakraborty and Das (2019), the experimental values, Taguchi model's values and utility concept's values of Kandpal et al. (2017).
7. The AHP (criteria weight) evaluation method prioritizes the factors as duty factor > pulse-on-time > peak current in the current paper. Such prioritization is absent in Chakraborty and Das (2019) and Kandpal et al. (2017) and compliments the prioritization efforts of this paper.

The present study shows results that are consistent with experimental results of Kandpal et al. (2017) and the outcomes of other researchers.

4.7. Contributions

First, the frameworks contributed serve as alternatives to the current approaches to optimization. Indeed, the Taguchi – Pareto and Taguchi–ABC, which are perspectives of how engineering processes could be concurrently optimized and prioritized and provides an extension to the classical Taguchi method limited to factor/lever determination, development of orthogonal arrays, computation of the signal-to-noise quotient and the evaluation of the optimal parametric settings for process parameters. By revealing how the joint optimization and prioritization may be achieved, the models explain the distinct positions of one factor against the other. Resources in the EDM process are scarce and should be prudently managed; no wastages due to over-allocation of resources to one factor are permitted as it distorts the likely performance of the organization from global to local optimal results. Although optimization of process parameters remains in portrait, prioritization influences the way optimization is made. Nonetheless, the EDM process engineer may be unconscious of prioritization influences on the machining decisions being pursued.

Second, this paper illuminates on the particular mechanism, which details out how the analytical hierarchy process may be applied in a unique manner, to prioritize the EDM process factors, showing that they are not of equal strength in computations and decision making. Despite the different weights of EDM process factors, research in this area has scantily investigated EDM process using multicriteria models. Consequently, many evaluations may have been misguided and wrong decisions made. This has restricted researches understanding on their influence and limited budgetary on their influence and limited budgetary purposes, which could have given more attention to particular factors.

5. CONCLUSIONS

In this article, three unique models, namely, the Taguchi-Pareto, Taguchi-ABC and analytical hierarchy process were promoted and validated using a chosen EDM process with the experimental investigation of previous researchers. The Taguchi–Pareto and Taguchi–ABC optimization approaches could concurrently prioritize and optimize the EDM process parameters of peak current, pulse-on-time and duty factor. So, associations are built up between the variables and the responses.

In conclusion, the following points are taken from the study:

- The application of Taguchi–Pareto and Taguchi–ABC is valid for the EDM process and sensible results obtained that prioritized the factors
- The Taguchi–Pareto ranked the process parameters in the order of importance at pulse-on-time > peak current > duty factor
- The Taguchi–ABC, which reduced to two factors B (Pulse-on-time) and C (Duty factor) ranked the parameters as duty factor > pulse-on-time
- The analytical hierarchy process ranked the parameters as duty factor (0.6651) > pulse-on-time (0.2311) > peak current (0.1038)
- Using the AHP, the consistency ratio (0.07) is less than 1, and the new approach of AHP, which is used to complement the prioritization by Taguchi–Pareto and Taguchi–ABC. Thus, the matrix obtained is consistent

An interesting observation is that the results drawn from the proposed Taguchi-Pareto, Taguchi-ABC and analytical hierarchy process have intimate agreements with the experimental results declared by previous researchers, such as Kandpal et al. (2017) and Chakraborty and Das (2019). Consequently, the Taguchi-Pareto, Taguchi-ABC and analytical hierarchy process can successfully direct the EDM process engineer to estimate the provisional values of the various responses while combining several parameters of the EDM process together. Those models may be successfully installed for the EDM processes of other composite materials and other manufacturing processes, including the traditional and non-traditional systems to estimate their utmost output accomplished in concurrence with quality machined product outputs and utmost efficiency of the machines. In the future efforts should include integrating to or more models such as fuzzy logic and Taguchi-Pareto, and fuzzy logic and Taguchi-ABC. Furthermore, the optimization result of this study can also be used for other metals and alloys apart from the AMMC. Examples of potential materials include the EDM of magnesium alloys, titanium alloys, copper alloys, and super-alloys.

6. REFERENCES

Arunachalam R., Piya S., Krishnan P.K., Muraliraja R., Christy J.V., Mourad A.I. and Al-Maharbi M. (2019) ‘Optimization of stir–squeeze casting parameters for production of metal matrix composites using a hybrid analytical hierarchy process–Taguchi-Grey approach’, Engineering Optimization, https://doi.org/10.1080/0305215X.2019.1639693

Ajibade O.A., Agunsoye J.O., Oke S.A. (2016) ‘Tapped density optimization for four agricultural wastes: Part II - Performance analysis, main effects of process parameters and Taguchi-Pareto’, Acta Periodica Technologica, Vol. 47, pp. 129-142.

Ajibade O.A., Agunsoye J.O., Oke S.A. (2019a) ‘Parametric ratio optimization and statistical modeling of wear performance in dual filler particle reinforced epoxy composites’, Kufa Journal of Engineering, Vol. 10, No 1, pp. 140-159

Ajibade O.A., Agunsoye J.O., Oke S.A. (2019b) ‘Optimization of water absorption parameters of dual–filler filled composites using Taguchi and moderated Taguchi techniques’, Kufa Journal of Engineering, Vol.10, No.2, pp. 134-151

Chakraborty S., Das P.P. (2019) ‘Fuzzy modeling and parametric analysis of non-traditional machining processes’, Management and Production Engineering Review, Vol. 10, No. 3, pp. 111–123. DOI: 10.24425/mper.2019.130504

Dey A., Debnath S., Pandey K. M. (2017) ‘Optimization of electrical discharge machining process parameters for Al6061/cenosphere composite using grey-based hybrid approach’, Transactions of Nonferrous Metals Society of China, Vol. 27, No. 5, pp. 998-1010

Dey A., Reddybandi V. R., Pandey K. M. (2018) ‘Wire electrical discharge machining characteristics of AA6061/cenosphere aluminium matrix composites using RSM’, Materials Today: Proceedings, Vol. 5, No. 1, pp. 1278-1285

Gangil M., Pradhan M. K. (2017) 'Modeling and optimization of electrical discharge machining process using RSM: A review', Materials Today: Proceedings, Vol. 4, No. 2, Part A, pp. 1752-1761

Gore A.S., Patil N.G. (2018) 'Wire electro discharge machining of metal matrix composites: A review', Procedia Manufacturing, Vol. 20, pp. 41-52

Gudipudi S., Nagamuthu S., Subbian K.S., Chilakalapalli S.P.R. (2019) 'Fabrication and experimental study to optimize the recast layer and the material removal in electric discharge machining (EDM) of AA6061-B4C composite', Materials Today: Proceedings, Vol. 19, No. 2, pp. 448-454

Hussein A.K., Abbas L.K., Hassan W.N. (2019) 'Optimization of steel hardness using nano fluids quenchants', Kufa Journal of Engineering, Vol.10, No.1, pp. 29-43

Kandpal B.C., Kumar J. and Singh H. (2017) 'Optimization and characterization of EDM of AA 6061/10%Al2O3 AMMC using Taguchi's approach and utility concept', Production and Manufacturing Research, Vol. 5, No. 1, pp. 351-370, doi:10.1080/21693277.2017.1389315

Kandpal B.C., Kumar J., Singh H. (2018) 'Optimization of electrical discharge machining AA6061/ 10 %Al2O3 composite using Taguchi optimization technique', Materials Today: Proceedings, Vol. 5, No. 9, Part 3, pp. 18946-18955

Kim Y.-S., Chu C.-N. (2018) 'The effects of graphite powder on tool wear in micro electrical discharge machining', Procedia CIRP, Vol. 68, pp. 553-558

Klocke F., Holsten M., Klink A. (2016) 'Technological and economic investigations on the application of metal infiltrated graphite electrodes for the sinking EDM of cemented carbides', Procedia CIRP, Vol. 42, pp. 632-637

Nwafor S.C., Oke S.A., Ayanladun C.A. (2019) 'Taguchi optimization of cast geometries for A356/organic particulate aluminium alloy composites using a two-phase casting process', Journal of Applied Science and Process Engineering, Vol. 6, No. 2, pp. 386-411.

Qattawi A., Mayyas A., Abdelhamid M. and Omar M.A. (2013) 'Incorporating quality function deployment and analytical hierarchy process in a knowledge-based system for automotive production line design', International Journal of Computer Integrated Manufacturing, Vol. 26, No. 9, pp. 839-856. https://doi.org/10.1080/0951192X.2013.799780

Samvedi A., Jain V. and Chan F.T.S. (2012) 'An integrated approach for machine tool selection using fuzzy analytical hierarchy process and grey relational analysis', International

Journal of Production Research, Vol. 50, No. 12, pp. 3211-3221. https://doi.org/10.1080/00207543.2011.560906

Siegel, E. (1965) 'Economic use of electrical discharge machining for research, production, and tooling through the design and construction of low cost electrodes', SAE Technical Paper 650021, https://doi.org/10.4271/650021.

Triantaphyllou E, Mann S.H. (1995) 'Using the analytic hierarchy process for decision making in engineering applications: some challenges', The International Journal of Industrial Engineering: Theory, Applications and Practice, Vol.2, No.1, pp. 35 – 44

Zhang Y., Xu Z., Wang Y., Ni Q., Ling X. (2019) 'Surface-improvement mechanism of hybrid electrochemical discharge process using variable-amplitude pulses', Chinese Journal of Aeronautics, In press, corrected proof