# Optimization of Wire Electrical Discharge Machining Parameters on AZ91 Magnesium Alloy Using Analytical Hierarchy Process-Taguchi-Based Analyses

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**Abstract.** *The Taguchi approach has substantially influenced the material subtraction industry in the past few decades. However, limited studies have applied the Taguchi, Taguchi-Pareto and Taguchi-ABC methods in electrical discharge machining (EDM) systems and no study has integrated the analytic hierarchy process to these methods in the context of EDM systems to process AZ91 magnesium alloy. The AZ91 magnesium alloy was chosen in this article due to its low weight, attractive corrosion resistance, low density, high strength, die-castability and potential for a wide range of industrial applications. The present authors attempted the above integrations and introduced the AHP method at the response table developmental phase of the Taguchi, Taguchi-Pareto and Taguchi-ABC methods. A key optimal parametric setting, AHP-Taguchi-Pareto is* $A_3B_3C_3D_1E_3F_3$ *which is interpreted as 126 units for a pulse on time, 60 units for pulse off time, and 230 units for pulse current, 20 units for gap voltage, 8 units for wire feed and 12 units for wire tension. Furthermore, the order of ranking of parameters according to the Taguchi and AHP-Taguchi methods coincides with 4/6 parameters, equivalent to 66.7%. A key ranking order of parameters according to the Taguchi and AHP-Taguchi-ABC Parts A, B and C coincide with 4/6 parameters, equivalent to 66.7% for the Taguchi-AHP-Taguchi-ABC Part A analysis. Based on the findings, it is concluded that by applying the AHP method to the Taguchi methods, it was possible to develop the optimised process values for the wire electrical discharge machining of AZ91 magnesium alloy material.*

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## 1. Introduction

The analytic hierarchy process (AHP) method and the Taguchi method have great and highly influential qualities, which appeal to researchers and process engineers [1],[2],[3]. The finding of previous studies indicates that the Taguchi method saves cost and time, and obtains superior surface characteristics [3] while the AHP method achieves higher industrial performance and productivity [1] and enhances machining performance [2]. Furthermore, the classical AHP method succeeds in classifying an extremely long list and challenging members of parameters, difficult to handle manually [1],[4],[5]. Thus, it organizes the parameters in a unique order of importance [4]. This has been extensively applied in welding [4],[6],[7] and machining [1],[2]. The Taguchi method on the other hand has recorded tremendous parameters while ensuring the economy of experimentation [3]. Despite this, the synergic benefit of both kinds of methods is hardly explored for the electrical discharge machining (EDM) process, to make the process more energy efficient [8],[9],[10]. Li and Kara [11] declared energy efficiency as a crucial issue in industries. However, using the two methods in adequate resource distribution and utilization schemes for energy-related parameters of the EDM process fulfils this purpose. Furthermore, while processing the AZ91 magnesium alloy in the EDM process, a scarcity of information is available about the synergy results of both methods in the literature. But the AZ91 magnesium is highly critical for structural development in the aerospace and automobile industries and should be given the utmost attention in new research investigations. At present, the AZ91 magnesium alloys are known to have low weight, attractive corrosion resistance, low density, high strength, die-castability and potential for a wide range of individual applications and hence chosen for investigation as the work material in this article.

To bridge the gap discussed in the proceeding discussion, the present article proposes an amalgamation of the AHP method and Taguchi methods (Taguchi, Taguchi-Pareto and Taguchi-ABC) to achieve substantial process improvements through the implementation of the optimal parametric settings developed from the amalgamation. The point of coupling the methods is the introduction of the AHP weights into the response table of the Taguchi, Taguchi-Pareto and Taguchi-ABC methods where the average signal-to-noise ratios have been completed. The results are the development of the delta values, ranks and optional parametric settings which could be interpreted. In this study, the integrated AHP-Taguchi, AHP-Taguchi-Pareto and AHP-Taguchi-ABC methods were formulated and evaluation was based on the literature data on EDM experiments reported by Muniappan et al. [12]. The amalgamation was done to see the benefit of this efficient integrative procedure from the viewpoint of the ability to concurrently prioritize parameters using the classical method and optimize these parameters for results, which serve as inputs into the manufacturing process. The impacts of the optimization using diverse methods were compared.

Besides, insights from the literature reveal that the development of parametric weights for EDM is a useful concept for planning for resource distribution during the planning phase of machining before embarking on the implementation stage. In the EDM process, performance optimization and the concern to selecting significant process parameters for the concentration of machining resources and production efforts are key promising sustainable tools. Besides, its potential to maintain the good health of the organization, the delivery of high-quality machined products is also the dividend of the EDM process. This is well pronounced in an era of stiff competition that promotes the performance of the process as a strong competitive weapon to establishing top players within the EDM industry. Therefore, the optimization and selection process within the EDM literature regarding the EDM process is needed. Furthermore, understanding the literature reveals that optimization is the need of the hour. Accordingly, from the review of papers in the EDM domain, it is clear that integrating multicriteria methods with the Taguchi method is a potential candidate to promote efficiency and correct judgment in the evaluation of the EDM process. This statement has been recently validated in a recent study that integrated the EDAS method and the Taguchi methods containing the classical Taguchi and Taguchi-Pareto methods [13]. To date, comparatively few reports have been given to demonstrate the synergic benefits of two or more methods involving multicriteria analysis and Taguchi optimization. Besides, it is extremely hard to find any detailed study associated with integrating the multicriteria method of the AHP and the Taguchi method for the important AZ91 magnesium alloy during the machining process using the EDM. Consequently, the present study provides a route to study the synergic behaviour of an integrated method of the AHP method and Taguchi method in the processing of the AZ91 magnesium alloy during the EDM process parametric determination.

From the foregoing, the novelty of this article could be stated as the amalgamation of the classical AHP method and each of the Taguchi method, Taguchi-Pareto and Taguchi-ABC methods to determine the optimal parametric setting of the AZ91 magnesium alloy while concurrently prioritizing the EDM process parameters and optimising them for efficient process control. However, to evaluate the correctness of the novelty claim in this article, the proposed methods of AHP-Taguchi, AHP-Taguchi-Pareto and AHP-Taguchi-ABC are compared with the conventional method of Taguchi.

## 2. Literature review

### 2.1 EDM

Tagged as a premier non-traditional machining approach, EDM has over the years proliferated into two main groups, namely the conventional and wire EDM systems. The technological development in the small-batch mould and die production industries for prototype making aided the expansion of the conventional EDM systems to a wide range such as the ram, die-sinkering, volume, sinker and cavity–type EDM varieties. As development progressed, the diverse materials that need to be processed such as super alloys, aluminium, steel, brass and titanium caused a radical expansion to produce the wire EDM system with huge accuracy. It then grew into varieties such as wire erosion and wire burning, and spark EDM. Undoubtedly, whether the conventional or the wire EDM type, the attraction of process engineers towards using the EDM systems is due to their numerous advantages in part tolerance, hardness, accuracy machining and the capability to precisely machine complicated part shapes and thin-walled structures.

### 2.2 AZ91 Magnesium alloy

Magnesium alloy, due to some of its outstanding features, has won a top position in the list of materials available for manufacturers to make their choice [14]. It is in high demand in industries such as the automobile and aerospace because of its mechanical and chemical properties and characteristics. (e.g. mechanical strength, low cost in production, low density, ability to be machined and cast and resistance to corrosion) [15]. Chung et al. [16] studied the microstructural and mechanical properties of an as-cast AZ91 magnesium alloy and discovered that although there could be some flaws in the material (in terms of the ductility and strength), they could be enhanced by refining their grains. Besides, they reported that an intense plastic deformation method, equal channel angular pressing (ECAP), could be employed in enhancing the strength and ductility of materials by reducing the size of the grain at a high temperature while applying some form of solutions.

Muniappan et al. [12] examined how to optimise WEDM process parameters on the machining response of an AZ91 magnesium alloy and noted that when small strength is required for fabricating large bulk of castings of the lightweight matrix, a high volume of die casting can be considered. They declared that most of the AZ91 magnesium alloys in use contain about aluminium, 9% and zinc, 1% while others would contain other metals such as copper, manganese, zinc and aluminium, zirconium and other silicon rare earth metals in varying proportions. Agarwal and Sahu [17] provided more insights into the constituents and the placement of magnesium in the industry. According to them, it is one of the lightest metals with a density of 1.74g/cc and produces a very high strength-to-weight ratio. Besides, they asserted that AZ91 magnesium alloy is one of the many variations of magnesium alloys that have been developed to overcome the limitations present in magnesium while maintaining its other microstructural and mechanical qualities. Furthermore, the variations of AZ91 magnesium alloy developed such as AZ91A, AZ91B, AZ91C, AZ91D and AZ91E are noticed to distinguish the class D as the most used due to its commercial availability and other unique properties and qualities. According to Muniappan et al. [12], magnesium takes the shape of a hexagonal cross-section and is mostly used as either wrought alloy or cast alloy.

Sunil et al. [18] when studying the joining of some selected grades of magnesium alloy using friction stir welding, made it clear that two different magnesium alloy grades can be joined together. They concluded by stating that friction stir welding is an effective method of joining magnesium alloy of various grades. Not just magnesium alloy but other metals and alloys which are difficult to machine. Prasad et al. [15] analyzed the corrosion behaviour of magnesium with the observation that whenever the element and its alloys are considered during an engineering design, due process must be followed to ensure that the material can overcome some of the limitations that might be present in the material to upgrade it to the required state where those limitations are dealt with.

Kudyba et al. [19] used a mechanical purification liquid alloy to enhance the wettability of AZ91 and evaluated the effect of purifying a molten alloy of magnesium mechanically using a boron carbide $B_4C$. They further observed that when the capillary procedure was utilized, the surface oxide was extracted when the molten AZ91 alloy was squeezed into a capillary tube. They concluded that a spontaneous infiltration process that is influenced by capillarity should be expected, and this can influence the efficiency of the outcome due to the absence of reactive products which could ruin the whole process. Chen et al. [20] used AZ91 magnesium alloy laminates for combined strength and ductility. They designed three laminates by piling layers of AZ91 extruded sheets at different stages to improve the mechanical properties in which they discovered that the combination of the treated sheets in solid-solution form plus ageing-treated sheets produced a high tensile strength of about 386 MPa and ductility of about 19.8%.

Guan et al. [21] studied the microstructure, wear resistance and mechanical properties of $SiC_p$/AZ91 (i.e. particulate silicon carbide mixed with magnesium alloy AZ91) composites using a vacuum pressure infiltration. They noted that particles of SiC bonded well with the metal matrix when uniformly distributed. They confirmed that $Mg_{17}Al_{12}$ gravitates towards the particle of SiC while inducing an unsuitable coefficient of thermal expansion between the particles of the silicon carbide and the AZ91 matrix which rapidly increases the ageing precipitation of the matrix. When compared with AZ91 Magnesium alloy, adding particles of SiC provides excellent wear resistance. Cai et al. [22] worked on the crack source of magnesium AZ91-09Gd alloy and its propagation, in which they analyzed the fracture mechanism and the crack source. They declared that what causes inter-granular fracture and poor plasticity in the alloy is the continuous distribution along with the grain network. When load increases, micro cracks begin to occur at the $Al_2Gd$ and $Mg_{17}Al_{12}$ and these cracks increase at a rapid rate and link up with other micro-cracks until it becomes major crack leading to failure.

Lei et al. [10] performed experimental research on the uniaxial cyclic plasticity of an AZ91 magnesium alloy in which various train and stress experiments at room temperature. They observed that cast AZ91 produces a pseudo-elastic behaviour when unloading as a result of untwining. They concluded that the result obtained depends largely on the chosen mean stress and strain amplitude, though, slight changes are observed when stressed and the responding max/min strain immensely differs for cast AZ91 Magnesium alloy as against wrought magnesium alloy. Shulha et al. [9] conducted an in situ formation of a layered double hydroxide (LDH) based nano-container on the surface of AZ91 Magnesium alloy. They concluded that a mixture of LDH-OH/$CO_3$ grows on the surface of the AZ91 Magnesium alloy when exposed to diethylenetriraminepentaacetic acid (DTPA) pentasodium salt. Al Bacha et al. [14] conducted research on the valorization of AZ91 through the hydrolysis reaction in the production of hydrogen. They observed that milling at a higher speed (350) produced a better reaction thereby improving the performance of the hydrolysis performance of the AZ91. They asserted also that out of the two additives, AlCl3 produces better hydrolysis performance with up to 65% of its $H_2$ generation capacity, while with graphite, about 75% of its $H_2$ generation capacity was achieved in a very short period.

## 2.3 Applications of AZ91 magnesium alloy

Prasad et al. [15] affirmed that magnesium was known for its advantage when used for structural purposes. This is due to some of its special mechanical and physical qualities such as low density, low corrosion resistance and ability to be combined with other metals to form various alloys. Furthermore, it is impressive that magnesium and its alloys have found applications in various fields such as automobile, aerospace, power, telecommunication, chemical storage and a whole lot of other industries some of which the wide-scale usage of AZ91 magnesium alloy is discussed as follows:

1. In the aerospace industries, Abderrazak et al. [23] declared the preference for AZ91 magnesium alloy

due to their elevated strength-to-weight proportions and superior thermal conductivity. This was demonstrated using the Nd: YAG laser beam welding experiments. The viewpoint which promotes the wide acceptance of AZ91 magnesium alloy was also raised by Dhahri et al. [24] for the aerospace industries. Furthermore, it is known that AZ91 magnesium alloy finds its use in the engine compartments, transmission units, gears and components of aerospace equipment. Additional attributes that make this alloy a preferred variety are its light nature and ability to resist corrosion.

2. Literature sources have also shown the usefulness of AZ91 magnesium alloy in the automotive industry. The twin material study of AZ91 and WE43 magnesium alloys by Dhahri et al. [24] during the laser welding process investigation confirms the utility of AZ91 magnesium alloy in automotive industries. Its common uses include engine blocks, steel tracks, wheels and dashboards. These are regarded as applications not sensitive to corrosion. Proponents of AZ91 magnesium alloy, including Dhahri et al. [24] argued that its use provides an opportunity to reduce the weight of automobiles and also improves the economic consumption of fuel.
3. In Li et al. [25], support was given to AZ91 composite as useful material for green environmental protection. It was argued that magnesium-oriented composites have the potential to adjust the wear resistance, and elastic modulus and elevate the temperature resistance of structures. An important conclusion is while adding rare earth Pr, growth in the ultimate tensile strength and yield strength of the AZ91 matrix was observed. Nonetheless, there was decay in the elongation of the AZ91 magnesium alloy.
4. In electronics, magnesium finds its applications in some power tools and components such as mobiles, cameras, rechargeable batteries and video players. Rashid et al. [26] addressed the contributions of AZ91 magnesium alloys to various industries, mentioning the electronics industry as one of the beneficiaries of laser-oriented machinery concerning the AZ91 magnesium alloy.
5. In the biomedical field, magnesium and its alloys find their applications in the treatment of fractured bones as they are sometimes infused into the human bones to strengthen them since they are non-toxic and biodegradable. Also, considering the long hours in which it would be used, the weight of the person using it is no longer an issue. Chen et al. [27] and Xin et al. [28] offered support for these statements by introducing AZ91 magnesium alloy in body fluid simulation (i.e. [28]) and to correct damaged bones (i.e. [27]).
6. In power tools for manufacturing, the lightweight attribute and ability to be manipulated into different sizes and shapes of magnesium alloy have been exploited. Accordingly, Lohmuller et al. [29] declared the use of magnesium alloys in injection moulding.
7. In storage devices, magnesium and its alloys are used for the construction of storage tanks or various chemicals such as hydrogen. The material could withstand the reaction of some gases at different temperatures. Other areas where one could use magnesium and its alloys include batteries. Song et al. [30] provided a review to support the use of magnesium alloys. In the review, storage devices such as Mg ion batteries and magnesium materials for hydrogen storage were pronounced to have attracted the significant attention of researchers and storage devices based on them have been used in practice.

## 2.4 Taguchi Method and its analysis

Nain et al. [31] investigated how to obtain the best solution to improve WEDM performance when working on a Udimet-L605 using a particle swarm optimization method, Taguchi's L27 orthogonal array, and the linear regression model to obtain an optimal combination. The particle swarm optimization method was used to obtain the best global solution for the desired output performance. They also observed that pulse on time is the most influencing factor on the cutting speed, the wire wear ratio and the dimensional deviation.

Ishfaq et al. [32] optimised the rate of cutting and the surface finish of an aluminium alloy Al6061 in a wired EDM process by minimizing the errors at the corner. They used Taguchi's L27 design in the work and the experimental result proved that angular error was influenced by wire tension with 25.5%, pulse off-time with 12%, and flushing pressure with 15.6%. Considering surface finishes, the material removal rate was achieved by the pulse on time with 15.3%, the open voltage at 28.5%, wire feed and the flushing pressure concerning the experiment were 13.2% and 10.7% respectively, with pulse longevity playing the most important role.

## 2.5 AHP optimising parameters

Carved out as a niche tool to arrange and examine complicated decisions in the management decision-making area, the utility of the analytic hierarchy process, AHP has expanded in boundaries to engineering decision making. Surprisingly, as the AHP extends in applications ranging from welding to machining to construction, it also expands in utility from a mere arrangement tool to one that could optimise parameters. The AHP tool, developed in the 1970s by Thomas Saaty has therefore been extended to optimization by the following authors. Achebo and Etin-osa [7] deployed the AHP to optimise the process parameters while welding low carbon steel material. The choice at the optimal point was weldment 7. In submerged arc welding, Sarker et al. [33] coupled the AHP and Taguchi method to optimise the welding parameters of that the influence of wire feed rate on the properties of the bead geometry is higher than other welding parameters.

Furthermore, Sabiruddin et al. [6] actualized the parametric optimization for the GMAW process using low carbon steel. It was concluded that yielded the maximum results with the welding speed of 370 min/min, welding voltage of 25 volts, and weight of 0.183. Besides, Liang and Yang [5] analysed the AHP approach with optimization features. The authors analysed the outcome from the general BOCR approach. Further successful analysis was made with the WASPAS method. In Tomashevskii [34], the rank reversal issue during optimization using the AHP was tackled. It was declared that weight function adjustments are best for the optimization methods. Putri and Mahmudy [35] established a procedure for optimising the selection of the correct tutoring outlet in a location using the integrated analytic hierarchy process and genetic algorithm. It was concluded that the method yielded superior results weighed against the deployment of AHP only.

From the discussion above, two groups of studies were reported: those that optimise the process parameters using the analytic hierarchy process alone and articles that recognize the drawbacks of the AHP and supported its use with optimization tools such as the Taguchi method [4], and genetic algorithm [35]. The principal drawbacks recognized by these researchers are the rank reversed problem which was solved accordingly by introducing the coupled optimization tools (i.e. Taguchi method and genetic algorithm). However, despite the utility of coupling the AHP method with optimization tools, the opportunity to exploit its benefits in EDM has not been reported in the literature. More specifically, the use of the AHP-Taguchi method to process AZ91 magnesium alloy has not been made. Yet, enormous amounts of AZ91 magnesium are processed day after day with a carry-over of this important gap, which should be resolved with utmost urgency.

## 3. Methods

Researchers on machining generally agree that EDM as a non-conventional form of machining has conditions that are distinct from the traditional metal removal system involving multiple tool contact with the material where material subtraction is done with material-tool contact under dry and wet conditions of lubrication. The EDM system is very expensive to purchase and faults are mostly cleared through replacements of expensive parts, which deeply affects manufacturing profits. Thus, practising engineers, process engineers and technicians in the EDM industry must tackle the multiple unique challenges that the upgraded technology has brought about in its daily operations. Therefore, this article proposes integrated Analytic hierarchy process-Taguchi technique methods in the form of three methods of Analytic hierarchy process method-Taguchi method (AHP-T), Analytic hierarchy process method-Taguchi-Pareto (AHP-TP) and Analytic hierarchy process method- Taguchi-ABC (AHP-TABC). In this section, the steps involved in the selection and implementation of the three methods are discussed. Hence the discussion commences with the TAHP method.

### 3.1 Choosing methods for evaluation

In this article, the objective is to evaluate the process parameters of the EDM process of the AZ91 magnesium alloy using the EDM process on the condition of concurrent optimization and prioritisation of the parameters. Consequently, several alternative tools may be considered for evaluation. However, it is not possible to utilize the whole universe of tools possible for this task and the very limited options of the analytic hierarchy process (AHP), Taguchi (T) method, Taguchi-Pareto (TP) method and Taguchi-ABC method. But to choose among these methods, some evaluation criteria need to be deployed. Here, several principles (i.e. evaluation criteria) are deployed to choose the superior method(s) that adequately tackle the problem of the EDM process parametric optimization and prioritisation.

*The study goal*: Evaluate using methods to optimise and choose the importance of specific criteria.
Possible solution routes:

1. *Taguchi method*: The philosophy used to establish the Taguchi method is that of ascertaining that the EDM process parameters are optimised through the elimination of the gap between the expected process parametric threshold and the currently achieved values of the parameters. Consequently, the Taguchi method optimises the EDM process parameters through the reduction of variations before the parametric optimization to strike the average mark of the EDM output parameters. This is accomplished by deploying a unique orthogonal matrix to evaluate and transform the signals from the process parameters using the least possible experimental trials.
2. *Analytic hierarchy process method*: The framework of the design for the AHP method is oriented around classifying and examining the complicated EDM process decision-making as advocated in the philosophy proposed by the notable scholar, Thomas L. Saaty during the 1970s. The principle of how the AHP method works are to first establish the EDM criteria and the possible choices and establish an association of the EDM system constituents to the complete goal of the EDM process.
3. *Analytic hierarchy process-Taguchi method*: The proposed AHP-Taguchi method in the context of the EDM process shows the benefits of the AHP and the Taguchi methods to the concurrent reduction of variations in the EDM process, by stimulating a vigorous experimental design and also classifies and examines the EDM decision process. Since the AHP

method is first mentioned in the AHP-Taguchi method synergy for the EDM process, the procedure for its implementation follows, first, identify the critical EDM process parameters to be analysed through criteria identification, define the possible choices and then establish an association of the EDM system constituents. This is the first phase of the method. The second phase utilizes the ordered parameters of the AHP method and their weights and follows the process delta value evaluation from its introduction at the response table mode of the Taguchi method. Finally, the optimal parametric settings of the EDM process parameters are determined and their ranks displayed.

4. *Analytic hierarchy process – Taguchi Pareto (AHP-TP) method*: This method exhibits a combination of two methods, namely the analytic hierarchy process and the Taguchi-Pareto method and demonstrates the capability to optimise the parameters through the Taguchi tool and to prioritize concurrently in a double-fold while using the AHP for the first fold of prioritization and the Pareto analysis for the second fold of prioritization. The AHP method aids in establishing the critical EDM process parameters to be examined through criteria identification, the definition of the probable choices and the establishing an association of the EDM system's constituents: This phase of evaluation using the AHP method is followed by the Taguchi-Pareto method that optimises and concurrently establish the significant causes of variations such that the EDM process could evade the use of or limit channelling resources to the parameters that are inefficient. Thus, the highest priority is given to efficient parameters. The advantage of this blending of AHP and Taguchi-Pareto methods is that while the process engineer in the EDM process attempts to optimise, there is a scope to focus on the parameters that demonstrate the greatest deliverables regarding the goal of the EDM system. To implement the Pareto analysis, the parameters that can attract 80% benefits to the system while considering only 20% of these parameters are voted as adequate candidates.
5. *Analytic hierarchy, process – Taguchi-ABC (AHP-TABC) method*: This method is a combination of two methods, namely the analytic hierarchy process and the Taguchi-ABC methods. This method shows the competence in optimising the EDM process parameters using the Taguchi tool while instituting the capability of the ABC method to manage the parameters more intimately and direct attention to parameters that have the greatest effect on the efficiency of the EDM process. Then the AHP complements the actions of the ABC method as a second prioritization tool through criteria identification, the definition of the possible choices and establishing an association of the EDM system's elements. Coupled with the AHP and Taguchi procedures, the ABC adds more strength to the association by first establishing all the essential parameters to produce an efficient EDM process. It then divides these parameters into capability pools that may be derived from the contributions of each parameter to the goal of the system. The assignment of each parametric capacity pool is made.

Furthermore, Table 1 shows the rating results by the present authors when confronted with the choice of method(s) for the concurrent optimization and prioritization of the EDM process parameters. The chosen method(s) should satisfy the goal of the EDM process i.e. to optimise and choose the importance of the specific criteria. From Table 1, five results are shown, and a value of 100% for each of the following methods was attained e.g. AHP-Taguchi, AHP-Taguchi-Pareto and AHP-Taguchi-ABC methods. Also, each of the AHP and Taguchi methods scored 60% and is not qualified for choice. Alternatively, all the three methods of AHP-Taguchi, AHP-Taguchi-Pareto and AHP-Taguchi-ABC methods that score 100% are chosen as the best choices for the concurrent optimization and prioritization of the EDM process parameters. However, the evaluation criteria principles used in the evaluation, displayed in Table 1, were drawn from the understanding of the limitation of previous studies, which the present study attempts to overcome.

| S/N | Evaluation Principle | E | F | G | H | I | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Can this approach tackle the goal of concurrent optimization and prioritization? | A | D | D | A | A | 1 | 0 | 0 | 1 | 1 |
| 2 | Can this method contain numerous parameters and concurrently optimise them? | A | D | A | A | A | 1 | 0 | 1 | 1 | 1 |
| 3 | Can the method deliver quantitative information when fewer experimental trials are considered? | A | D | A | A | A | 1 | 0 | 1 | 1 | 1 |

Key: A- Agree, D – Disagree, E - AHP-Taguchi, F – AHP, G – Taguchi, H - AHP-Taguchi Pareto, I - AHP-Taguchi ABC, 0 – binary code for agreement, 1 – binary code for disagreement

**Table 1** Weighing the AHP-Taguchi method against the AHP method and Taguchi method for the EDM process

| S/N | Evaluation Principle | E | F | G | H | I | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | Is the method capable of delivering the precise metric of measurement expected from the EDM process? | A | D | D | A | A | 1 | 0 | 0 | 1 | 1 |
| 5 | Is the method appropriate for several uses | A | A | A | A | A | 1 | 1 | 1 | 1 | 1 |
| 6 | Does it produce efficient results (easy to use)? | A | A | A | A | A | 1 | 1 | 1 | 1 | 1 |
| 7 | Is it possible to use several criteria for the EDM process | A | A | A | A | A | 1 | 1 | 1 | 1 | 1 |
| 8 | Is the method capable of selecting the importance of specific criteria | A | A | D | A | A | 1 | 1 | 0 | 1 | 1 |
| 9 | Does it have a mechanism to evaluate its consistency? | A | A | D | A | A | 1 | 1 | 0 | 1 | 1 |
| 10 | Is the method with a proven formula? | A | A | A | A | A | 1 | 1 | 1 | 1 | 1 |
| | Evaluation | 10/10 | 6/10 | 6/10 | 10/10 | 10/10 | - | - | - | - | - |

Key: A- Agree, D – Disagree, E - AHP-Taguchi, F – AHP, G – Taguchi, H - AHP-Taguchi Pareto, I - AHP-Taguchi ABC, 0 – binary code for agreement, 1 – binary code for disagreement

**Table 1** (cont'd). Weighing the AHP-Taguchi method against the AHP method and Taguchi method for the EDM process

These include the difficulty to utilize several parameters of the EDM process concurrently, reducing experiments to deliver results to a few and selecting parameters according to the importance of specific criteria after being optimised. Thus, it is argued that to overcome these barriers, three methods, namely AHP-Taguchi, AHP-Taguchi-Pareto and AHP-Taguchi-ABC, which have been shown in Table 1 to demonstrate a higher acceptance rate (i.e. 100%) should be used in the present study. Besides, this article chooses the three methods and not either the AHP method or the Taguchi method because they are different from these two methods in several ways. They combine the ease of application, and capability to choose the importance of specific criteria with the ability to incorporate several parameters while optimising and providing both quantitative and qualitative information for decision making, which are attributes that the Taguchi method brings into the synergy.

Besides, to understand the association between pairs of methods such as AHP-T VS AHP, AHP-T vs T, AHP-TP vs AHP, AHP-TP vs T, AHP-TABC vs AHP, and AHP-TABC vs T, chi-square analysis was performed based on the null hypothesis, Ho, that declares that the variable along the row and column are independent. However, the alternative hypothesis, Hi declares the dependence of the row and column variable. The test was performed for each pair of methods and the results are as follows. For all the pairs of methods tested, each comparison, represented as 1 to agree and 0 to disagree, showed a chi-square value of 3.2000, degree of freedom of 9 and p-value of 0.9558 and rows x columns of 10 x 2. Since $p>0.05$, the null hypothesis is accepted that the first variable (i.e. AHP-T). Thus, to summarize the results, for each of the six pairs of testing, i.e. AHP-T vs AHP, AHP-T vs T, AHP-TP vs AHP, AHP-TP vs T, AHP-TABC vs AHP and AHP-TABC vs T, the first variable is always independent of the second one. This validates the earlier claim in this section that AHP and T are not appropriate methods to solve the present problem of concurrent optimization and prioritization of the EDM parameters while using the AZ91 magnesium alloy as the work material. However, the suggested methods are the AHP-T, AHP-TP and AHP-TABC.

## 3.2 EDM fundamentals

In this article, the modified Taguchi method regarding the aspect ratios was applied to experimental data obtained from Muniappan et al. [12] and the outcome of the analysis is presented and discussed in this section. However, from the understanding of what each of the parameters of this work means in practical terms, in this study, six parameters are considered as obtained from Muniappan et al. [12], namely, pulse on-time pulse off time, pulse current, gap voltage, wire feed and wire tension. It is essential to describe what each of these factors means and the purpose of each of the factors. At a point in time in this study, each of the parameters is represented by a symbol. A, B, C, D, E and F are represented as a pulse on time, pulse off time, pules current, gap voltage, and wire feed wire tension, respectively. Briefly, in the following discussion, an explanation of what each parameter stands for and the functions is made. The pulse on time stands for the duration (timing) within which current is applied to the workpiece. This parameter is important for work to be done as it is during the time that work is implemented in the EDM process.

Next, is the pulse off time, which is the period in which the electric current is relaxed (withdrawn) from the work done. In that period, the purpose could be either to adjust the electrode or to rest the process. In essence, it is the time gap between the working and off-working period in the EDM process. However, it is essential to understand the importance of withdrawing electric current. The current is withdrawn for several reasons, including the need to reposition the electrode. Second, because there is no work to be done and the operator wants to relax the machine, the current can be withdrawn. Third, the need to re-strategize may lead to the withdrawal of current. During the process of machining, if the process engineer perceives that a new concept can be introduced then the current can be withdrawn. This may involve the process engineer deciding on what other options can be introduced into the work.

Fourth, current can be withdrawn when the process engineer notices that the operator is drifting out of plan or design and so, to check the master plan and correct the mistake. Fifth, at a point in time, assuming the current working with heads to reaching the bottom of the table, it can be withdrawn and adjusted so that the operator will not over drill. The above are the reasons why pulse off-time is important in the processing of the AZ91 magnesium alloy workpiece in the wire EDM system. Furthermore, the next factor is pulse current, which is measured in ampere. Pulse current is the required energy to perform the machining process. Recall in the previous discussion on the pulse on time. During this time, what is applied is the current. it is important because without it the work cannot be done. The next factor is gap voltage, which is the distance between the electrode and the workpiece and this distance should be maintained for the quality output of the machined component. It is important to maintain this distance so that uniformity could be maintained at the end of the working process.

Fluctuating the distance while processing the AZ91 magnesium alloy during machining can change the whole results. For instance, if the operator wants to drill in a straight line, a particular gap voltage must be maintained for this objective to be achieved and the uniformity of the straight line drilling is revealed. This means that at the beginning of the drilling, there will not be a depth of 5mins, for instance, and at the end, a different depth of more or less depth is attained. This is the interpretation of uniformity while working with the workpiece. The next factor is the wire feed, which is the depth at which the cut is being done. For instance, if the operator decides to use a depth of 2mm, this becomes the wire feed. The significance of wire is required for a cut operation to take place. The explanation of this factor may be better understood from this perspective. This depends on the applied current at the start. If the operator is using the higher gap current for a start, then the gap voltage may have to be increased to have the desired processing quality of the workpiece.

In this case, the damage will not be done to the workpiece. For instance, if 2 mm is picked as the wire feed, other parameters need to be synchronized to achieve the desired quality for the workpiece. Here the operators need to be sure that the applied current will not be too high concerning the gap voltage so that more than the desired feed will not be cut. In welding, the wire feed is seen relative to the soldering used. However, in drilling, it is the depth at which you are drilling the material. The next factor is wire tension, which is the overall load on the current-carrying conductor tool, the cable from which energy is taken from the source to the machine. If the tension in the wire is much it will cause an overheating in the wire. This is similar to using a 1mm cable to power a hot plate, for instance, this 1mm cable is not up to the expected requirement. It will burn the cable or damage the machine. Thus, wire tension is the required load that is expected from the wire supplying energy to the machine. It should not be less or more but just adequate to protect the functioning of the machine.

## 3.3. The AHP-T method

To apply the AHP-T method in the EDM process context in the production of a material, from the conceptualization of the factor-level table definition to the establishment of the optimal parametric setting, every step demands a careful implementation. Thus, the AHP-T method involves the following steps:

*Step 1*: Conceive the factor-level table by extracting the most important and representative factors for the EDM system. Then decide on the suitable levels that represent the conditions of the factors. The term factor (parameter) in wire EDM represents a measurable quantity to explain the inputs invested into the process to economically process a material. Parameters are often associated with the required resources to make the process run efficiently. They describe the characteristics of the EDM process, which can cut complicated cavities or contours in materials excluding the necessity for heat treatment for easy cutting/ processing of the materials. The level represents phases of the parameters with each phase representing a different attribute of the parameters. However, they are presented quantitatively.

*Step 2:* Establish the orthogonal array for the conceived factors and levels by ensuring that the member of factors and levels matches the standard orthogonal array provided by the software used. Sometimes non-matches of factors and levels with the standard requires revisions of levels and factors. The common experience is to reduce these two items to match the standard.

*Step 3:* Determination of the appropriate signal-to-noise criterion/criteria and the computation of the signal-to-noise indices. To determine the criterion for the signal-to-noise ratio to use for the generality of the factors, each factor is examined in its response when it is increased or decreased within the system. For instance, the researcher needs to query what the response of the parameter will be when increased and know if it will be beneficial to the system or not or if an increase in the value of a system's parameter will have a negative consequence on the system, then the smaller the better or the nominal-the-best is chosen. But further questioning will eliminate one of these criteria if no changes in the behaviour of the system are observed then the nominal best criterion is chosen, otherwise, the smaller the better criterion is appropriate. Furthermore, if an increase in a system's parameter will cause an increase in the response of the system, then the larger-the-better criterion is chosen. Then use one or more criteria to evaluate the factors at once to determine the signal-to-noise ratios.

The formula for the signal-to-noise ratio used in the present work is the smaller the better criterion, Equation (1)

$$S/N = -10 \log_{10} \frac{1}{n}\sum_{i=1}^{n} y_i^2 \quad (1)$$

Where $n$ is the number of parameters considered in the operation and $y_i^2$ is the square of the parameters

*Step 4:* Establish the average signal-to-noise ratios (response table). This is accomplished by focusing on one factor and a level at a time. At this time, the index representing the orthogonal array is traced from the table containing the orthogonal array specification. The corresponding signal-to-noise ratios to the orthogonal index are summed up and averaged to be representative values of the average signal-to-noise value for a particular factor under the specified level.

*Step 5*: Create a hierarchical structure in which the goal is kept constant at the top, the attributes/criteria occupy the second level while the alternatives strive to occupy the next level.

*Step 6:* Create a pairwise comparison matrix and adopt a scale of related components with the following remarks. 1 is equal importance, 3 is moderate importance, and 5 is strong importance.

*Step 7:* Design and administer questionnaires among those with relevant experience in welding, material science and material processing. These questions should answer the question of how important one parameter is to another.

*Step 8:* Summarize the questionnaire outcome inform of weights for each factor

*Step 9:* Extend the response table to incorporate an AHP weighting scheme and multiple the AHP weights for each factor with the corresponding signal-to-noise averages along each row.

*Step 10:* Interprete the optimal parametric setting by referring to the initial factor-level table and then reading the values in the cells of the optimal readings from the factor-level table. Also, define the ranks and the delta values from the response table.

## 3.4 The AHP-TP method

Since multiple parameters are involved in the actualization of the EDM process, the process engineer should identify what parameters are the most important ones and focus the resource distribution among these parameters after eliminating the less important parameters. Thus, the AHP-TP, which contains the Taguchi-Pareto method has the mechanism of identifying the important parameters within the EDM system by activating the Pareto component of the Taguchi-Pareto method. The following steps are relevant to implementing the AHP-TP method.

*Step 1*: Follow steps 1 to 3 of the AHP-T method to initiate the AHP-TP scheme.

*Step 2:* Institute the Pareto 80-20 rule whereby the complete set of the experimental trials is reduced by eliminating the less relevant items of the experimental dataset.

*Step 3:* Step 3: Institute step 4 of the AHP-T method.

*Step 4:* Implement steps 5 to step 10 of the AHP-T method.

## 3.5 The AHP-TABC method

Process engineers within the EDM system are subjected to the management of multiple parameters of the EDM system, which must be properly managed to achieve the utmost system benefits. This implies that concentration on these parameters should be equal as some parameters may contribute less to the goal of the EDM system than others. In this perspective, the process engineer needs to implement the AHP-TABC scheme to achieve the EDM system's goals of profit maximization. It is implemented as follows:

*Step 1*: Follow step 1 of the AHP-TP method.

*Step 2:* Institute the ABC classification scheme of inventory such that the parameters are grouped as A (most important, B (less important) and C (least important) parameters according to the percentage ranges of 1-69%, 70-79% and 80-100%.

*Step 3:* Step 3: Institute step 4 of the AHP-T method.

## 3.6 Criterion weight evaluation

The following formula gives the approach to evaluating the criterion weight for each parameter

$$CW = \frac{\sum(values of\ the\ criterion weight)}{n} \quad (2)$$

Where $n$ is the number of criteria

# 4. Results and discussion

## 4.1 Some details about Muniappan et al. [12] and our study results

This study used the experimental data of Muniappan et al. [12], which was conducted to establish the likelihood of obtaining optimal wire EDM process while focusing on the kerf width and cutting speed and using the AZ91 magnesium alloy as the working material. The multi-objective optimization by ratio analysis (MOORA) was deployed as an assessment tool. In this study, the kerf width and cutting speed are the central responses analysed. The kerf width is the width of art in the wire EDM process; it is an outcome of the process of removing the AZ91 magnesium alloy material in the wire EDM process. Also referred to as the working gap, it is calculated by first making a piece having a defined length and afterwards evaluating the real length. Then by observing that the square part is 90%, 10% stands as the kerf width.

The significance of the kerf width is appreciated in wire EDM according to the following explanation. As the gap distance is maintained between the AZ91 magnesium alloy and the wire electrode, there is decay in the dimension of the kerf width while the materials cutting width reduces. However, the working gap's width changes depending on the various cutting parameters considered the properties of the material being processed (i.e. AZ91 magnesium in alloy) and the dielectric fluid utilised in the wire EDM process. The cutting speed describes the speed differential occurring between the wire cutting element of the wire EDM and the surface of the magnesium ally worked on. Over the years, the technology of cutting using EDM has revolutionized by increasing the speed of cutting radically from roughly 3 to 4 square inches per hour in the early 1980s to roughly 17 square inches per hour in the 1990s. The threshold of speed nowadays is probably unprecedented. In this article, six process parameters based on four electrical controls and two non-electrical control process parameters were used by Muniappan et al. [12].

Electrical controls are physical interfaces of the wire EDM device that affects the characteristics of responses such as the kerf width and cutting speed and the process parameters specified for the system. Since the wire EDM process contains both electrical and non-electrical controls, unbiased modelling and evaluation of the wire EDM process performance may only be obtained if the parameters of evaluation are spread over the two aspects of electrical and non-electrical controls as Muniappian et al. [12] decided to do.

The considered parameters are the pulse on time (A), the pulse of time (B), pulse current (C) as well gap voltage (D), which are electrical control process parameters. Additionally, parameters are wire drum (E) and wire tension (E), grouped as non-electrical control process parameters. The probable reasons for choosing pulse on time, pulse off time, current and control speed is because these parameters are common and with wide applications in wire EDM systems. Three levels were formed by Muniappian et al. [12] for computational convenience. The experimental setup was on a CNC wire EDM of the brand Electronica Sprint. This choice of machine was made because of its comparatively low energy consumption, efficient processing capability and ease of maintenance regarding spare replacements. In the system, while flashes occur in between the AZ91 magnesium alloy and the wire terminal, the expulsion of the AZ91 magnesium alloy is achieved through a continuous distinct flash appearing towards the machining zone by an elector-warm system [12]. Besides, the miniature particles machined are conducted aside from the constant flow [12]. A stick placed exactly at the bottom and top of the AZ91 magnesium alloy holds the wire [12].

Muniappan et al.'s [12] experiment used a sample size of a rectangular plate being 100 x 1000 x 10mm and 0.25 diameter of brass. The authors used deionized water as the dielectric fluid under ambient conditions. This water helps to monitor and control the heat intake and the electrical discharge during the wire EDM process. Accordingly, the water substance is the crucial determinant of the level of the material removal rate from the AZ91 magnesium alloy and the final surface finish obtained on the parts. In Muniappan et al. [12], cleaning of the final part was achieved using an acid after all the experimental stages. It was noticed that after experimentation, Muniappan et al [12] deployed the MOORA to optimise the parameters for optimum kerf width and cutting speed. However, the present study diverges from the work by using a combination of AHP and Taguchi variant methods.

The above details are from Muniappan et al. [12] and provide useful information to validate the models proposed in this work. For the analytic hierarchy process, decision-making computations are based on the judgments of experts who are professionals in EDM technology. Then based on the parameters defined by Muniappan et al. [12], the hybrid AHP-Taguchi techniques comprising of AHP-Taguchi, AHP-Taguchi-Pareto and AHP-Taguchi-ABC methods are used in the present study.

Furthermore, the starting point of the analysis is to develop the factor-level table, which was obtained from the experimental data of Muniappan et al. [12] (Table 2). The experimental values utilized in this research work were extracted from Muniappan et al. [12] as shown in Table 2.

| Levels/Symbols | Pulse on Time (A) | Pulse off-time (B) | Pulse current (C) | Voltage gap (D) | Wire feed (E) | Wire tension (F) |
|---|---|---|---|---|---|---|
| Level 1 | 106 | 40 | 70 | 20 | 4 | 4 |
| Level 2 | 116 | 50 | 150 | 30 | 6 | 8 |
| Level 3 | 126 | 60 | 230 | 40 | 8 | 12 |

**Table 2** Process Parameters and their levels [12]

Where A is the pulse on time in (µs), B is the pulse off time in (µs), C is pulsed current in (A), D is gap voltage (V), and E is the wire feed (m/min) and F is the wire tension in (mm)

It was created from an experimental work done by Muniappan et al. [12]. The table contains machining control variables as a result of some experiments carried out by the authors. In Muniappan et al. [12], the authors attempted to enhance responses by considering outputs such as cutting speed and the Kerf width. These outcomes were optimised to obtain better efficiency for the system. However, in the present paper, a different approach is followed where those responses are not specially considered but assumed to be influenced by the results obtained in this article. Furthermore, it is important to note that certain parameters would be represented by alphabets so that wherever they appear we would understand what they stand for. They are alphabets A, B, C, D, E and F. The values in Table 2 are the inputs of process parameters carried during the optimization procedure. The table involves factors and levels. However, factors and levels are qualitative and quantitative terms used to explain the combinational sequence of importance while conducting experiments to establish the process parameters for the EDM of AZ91 magnesium alloys. Factors are the representative inputs in the wire EDM process that are combined with levels, which designate leadership in quantitative measurements within factors. As the level increases, the magnitude of the leadership of a factor in quantitative terms also increases. Levels are a second class of inputs in the wire EDM process whose combination with factors produces orthogonal arrays, which are outputs used to arrange the factors influencing the selected wire EDM process with the associated levels.

After the factor-level table, the researchers proceeded to use the Taguchi analysis process to obtain an optimised result. It is a way of analyzing an array of parameters to obtain optimality. Then the work proceeded by using the Minitab 18 (2020) software whereby these parameters are used in a way to split them into an orthogonal array using the L27 matrix. Then, the researchers introduced the signal-to-noise ratio formula and then analyze them in a table that interprets and brings out the values of the terms required to come up with the signal-to-noise ratios. The formula for the signal-to-noise ratio previously mentioned in the section on methods, which represents the smaller the better criterion was deployed in this work. The smaller the better criterion is one of the three criteria used for signal-to-noise ratio computation. The smaller the better criterion was deployed as smaller values of parameters favour the method. Besides, by approaching the work from the Taguchi perspective, the L27 orthogonal array is applied from the aspect ratio table of the formulation generated and using Minitab 18 (2020) software, Table 3. Also, the factors used here are six because, during the calculation, we considered the value for a parameter by extracting values from our reference material. As for levels, we considered three. The authors decided to use the L27 orthogonal array in the experiment to get a higher degree of accuracy.

| Exp. No. | A | B | C | D | E | F | A | B | C | D | E | F | $-10\log(1/n)\sum Y_i^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 106 | 40 | 70 | 20 | 4 | 4 | -34.8116 |
| 2 | 1 | 1 | 1 | 1 | 2 | 2 | 106 | 40 | 70 | 20 | 6 | 8 | -34.8278 |
| 3 | 1 | 1 | 1 | 1 | 3 | 3 | 106 | 40 | 70 | 20 | 8 | 12 | -34.8534 |
| 4 | 1 | 2 | 2 | 2 | 1 | 1 | 106 | 50 | 150 | 30 | 4 | 4 | -37.9202 |
| 5 | 1 | 2 | 2 | 2 | 2 | 2 | 106 | 50 | 150 | 30 | 6 | 8 | -37.9281 |
| 6 | 1 | 2 | 2 | 2 | 3 | 3 | 106 | 50 | 150 | 30 | 8 | 12 | -37.9407 |
| 7 | 1 | 3 | 3 | 3 | 1 | 1 | 106 | 60 | 230 | 40 | 4 | 4 | -40.6301 |
| 8 | 1 | 3 | 3 | 3 | 2 | 2 | 106 | 60 | 230 | 40 | 6 | 8 | -40.6343 |
| 9 | 1 | 3 | 3 | 3 | 3 | 3 | 106 | 60 | 230 | 40 | 8 | 12 | -40.6411 |
| 10 | 2 | 1 | 2 | 3 | 1 | 2 | 116 | 40 | 150 | 40 | 4 | 8 | -38.1553 |
| 11 | 2 | 1 | 2 | 3 | 2 | 3 | 116 | 40 | 150 | 40 | 6 | 12 | -38.1664 |
| 12 | 2 | 1 | 2 | 3 | 3 | 1 | 116 | 40 | 150 | 40 | 8 | 4 | -38.1553 |
| 13 | 2 | 2 | 3 | 1 | 1 | 2 | 116 | 50 | 230 | 20 | 4 | 8 | -40.6281 |
| 14 | 2 | 2 | 3 | 1 | 2 | 3 | 116 | 50 | 230 | 20 | 6 | 12 | -40.6343 |
| 15 | 2 | 2 | 3 | 1 | 3 | 1 | 116 | 50 | 230 | 20 | 8 | 4 | -40.6281 |
| 16 | 2 | 3 | 1 | 2 | 1 | 2 | 116 | 60 | 70 | 30 | 4 | 8 | -35.8237 |
| 17 | 2 | 3 | 1 | 2 | 2 | 3 | 116 | 60 | 70 | 30 | 6 | 12 | -35.8426 |
| 18 | 2 | 3 | 1 | 2 | 3 | 1 | 116 | 60 | 70 | 30 | 8 | 4 | -35.8237 |
| 19 | 3 | 1 | 3 | 2 | 1 | 3 | 126 | 40 | 230 | 30 | 4 | 12 | -40.7577 |
| 20 | 3 | 1 | 3 | 2 | 2 | 1 | 126 | 40 | 230 | 30 | 6 | 4 | -40.7511 |
| 21 | 3 | 1 | 3 | 2 | 3 | 2 | 126 | 40 | 230 | 30 | 8 | 8 | -40.7557 |
| 22 | 3 | 2 | 1 | 3 | 1 | 3 | 126 | 50 | 70 | 40 | 4 | 12 | -36.2041 |
| 23 | 3 | 2 | 1 | 3 | 2 | 1 | 126 | 50 | 70 | 40 | 6 | 4 | -36.1854 |
| 24 | 3 | 2 | 1 | 3 | 3 | 2 | 126 | 50 | 70 | 40 | 8 | 8 | -36.1986 |
| 25 | 3 | 3 | 2 | 1 | 1 | 3 | 126 | 60 | 150 | 20 | 4 | 12 | -38.5061 |
| 26 | 3 | 3 | 2 | 1 | 2 | 1 | 126 | 60 | 150 | 20 | 6 | 4 | -38.4950 |
| 27 | 3 | 3 | 2 | 1 | 3 | 2 | 126 | 60 | 150 | 20 | 8 | 8 | -38.5028 |

**Table 3** L27 orthogonal array for the problem studied [12]

From this point, after bringing out the results from the signal-to-noise ratio table, the authors proceeded to use the analytical hierarchy process for the results that were obtained from the administered questionnaire (see appendix). In this AHP method, the values obtained for each factor are the average of the total number of questionnaires administered for this work. The authors were able to come up with fifteen filled questionnaires. At this point, it is essential to discuss how the questionnaires were developed before printing and distributing them. It is interesting to note that before the design of the questionnaires the author studied the analytic hierarchy process and understood that to work using the method there is a need to rank the parameters according to an order of importance. So, the authors then picked the parameters of interest from Muniappan et al. [12] and drafted the questionnaires based on these parameters.

The duration of the survey is between August 2021 and March 2022 and the sources span two states in Nigeria, which are Lagos and Ogun. However, the target audiences for these questionnaires are professionals from various fields. These are different people who have acquired experience over the years. These include welders, design experts, engineers and end users of various machines. These are those who are involved mostly in design and production using various production machines like electrical discharge, laser machining, fusion welding machines etc. but they are knowledgeable on EDM. These respondents are not necessarily with high-ranking certificates such as master's degrees and doctorates. However, by experience, they have been exposed to using these machines over the years. They have a good understanding of the principles of these machines. Besides, one may ask if they have understanding enough to contribute to the questionnaires.

Certainly, because these people have an understanding of the principles of operation of the wire EDM machines they have contributed to our questionnaires. Although not all have been exposed significantly to the wire EDM machine they know about it and have been exposed to similar machines. These similar machines include laser machines and printing machines that print on metal sheets. During the survey, to assess the behaviour of the respondents, a lot of them contributed without difficulty in understanding the questionnaires. Also, some respondents decline to contribute based on the argument that their experience is not rich enough to claim to be an expert in a wire EDM parametric assessment. Based on their bias, the questionnaires were collected from them without being filled.

In these questionnaires, the authors were asking about the importance of one parameter over the others. Those parameters include pulse on time, pulse off time, pulse current, gap voltage and wire tension. For instance, the authors asked what importance the pulse on time over pulse off time is. The authors then assigned 0 as no importance, 1 as equal importance, 2 as moderate importance and 3 as strong importance. In the questionnaires, 15 questions were designed in all and they were administered to 30 respondents but only 15 questionnaires from those returned are useful. There were no responses from some of the respondents as they claim that they do not have a prior understanding of EDM. Drafting of 15 questions was done in the questionnaires deliberately reduced from 30 questions. The reduction in the number of questionnaires was made based on 2 reasons. First, if the questionnaire is too bulky, it will be difficult to get the respondents to fill the questionnaire. They will be discouraged to fill it at the first sight. Second, while studying the analytical hierarchy process, the researchers understood that for parameters for which some importance was obtained, the researcher can inverse it for the others. For instance, if the question had targeted knowing the importance of pulse on-time over pulse off time, the researcher is also supposed to ask in the questionnaire what is the importance of vice-versa i.e. pulse off time over pulse on time.

However, because the researchers do not want to ask the two questions, which may look confusing to the respondents, the researchers decided to skip the latter question to serve as the answer to the second. Furthermore, if 2 is obtained for the importance of pulse on-time over pulse off time, the answer for the second one is 1/2, which is the inverse of the first one (i.e. the reciprocal). Thus, with the questions, the researchers were able to gather about filled questionnaires filled by fifteen respondents out of the several that were administered. To move forward, the sum of the values obtained for each parameter was made and the average was found. To cite an example, consider the data obtained from the questionnaire when the relative importance of parameters is the pulse on-time over pulse off time. The first respondent filled 2, the second, third, fourth, fifth and sixth to the fifteen respondents filled the following respectively: 3, 2, 2, 2, 2, 2, 1, 1, 3, 2, 2, 2, 2, 1, respectively. These numbers averaged 29/15 i.e. 1.93. The fifteen at the denominator means the number of respondents. In practice, one may encounter a situation in which one or more respondents out of the fifteen respondents failed to give judgment on a question.

Although that is not the case in this situation, however, if this happens, the researcher is meant to remove the blank question from the computation in which the average will depend on the number of respondents that filled a particular question in the questionnaire. For instance, for the first question, if only thirteen respondents filled the questionnaire, the average of thirteen is rewarded. Furthermore, there are two things the present researcher will recommend to future researchers on this subject concerning questionnaire administration. It is recommended that the researcher should be present while the respondents were filling out the questionnaires. Thus if there is a question that the respondent is not clear with, the researcher should try to explain it in the simplest term that is understandable. By so doing, the respondent has an idea and now fills one of the options for the question that the respondent initially wanted to ship.

The second issue is the researcher should also make out time to summarize the questions to a few possibilities so that the respondents will be interested in filling the questionnaire honestly. With few questions, there is a likelihood of the respondents helping the researchers to fill the questionnaire. However, notice that respondents are professionals who are busy in their place of work and have very little time to spare. Then, the researcher has to be there for the respondent to fill in the questionnaire. If sometimes, it may require spending some waiting time before the respondent could give the researcher an audience. In that case, the researcher should be willing to spend their time waiting for the questionnaire to be filled. This has to be factored into the plan since without observing this, the researcher may not get many respondents to fill out the questionnaires. Therefore, the researcher needs to have the same sound skills in relating with the respondents to achieve the goal of the questionnaire design and administration. Sound skill is essential to help researcher relate and get them to fill the questionnaires.

The next stage of the analysis is averaging the total responses that were gathered. This is presented in a table termed the pairwise comparison matrix table for the value obtained during administering questionnaires for this work, Table 4.

| Labels | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| A | 1.0000 | 1.9333 | 1.6667 | 1.8000 | 1.8000 | 2.1333 |
| B | 0.5778 | 1.0000 | 1.3333 | 1.4667 | 1.0667 | 1.7333 |
| C | 0.7556 | 0.3778 | 1.0000 | 1.8000 | 1.8667 | 2.2667 |
| D | 0.6444 | 0.5111 | 0.6889 | 1.0000 | 1.6667 | 1.5333 |
| E | 0.6889 | 0.3889 | 0.5556 | 0.6333 | 1.0000 | 1.4667 |
| F | 0.5222 | 0.4778 | 0.5000 | 0.7111 | 0.6667 | 1.0000 |
| Total across rows | 4.1889 | 4.6889 | 5.7444 | 7.4111 | 8.0667 | 10.1333 |

**Table 4** Pairwise comparison matrix table for the value obtained

Then Table 5 is the normalized pairwise comparison table, which is a summarization of each column. This leads to the next table, which is calculating the normalized pairwise matrix where each of the values obtained in the proceeding table is divided by the total that was obtained.

| Labels | A | B | C | D | E | F | Criterion weight |
|---|---|---|---|---|---|---|---|
| A | 0.2387 | 0.4123 | 0.2901 | 0.2429 | 0.2231 | 0.2105 | 0.2696 |
| B | 0.1379 | 0.2133 | 0.2321 | 0.1979 | 0.1322 | 0.1711 | 0.1807 |
| C | 0.1804 | 0.0806 | 0.1741 | 0.2429 | 0.2314 | 0.2237 | 0.1888 |
| D | 0.1538 | 0.1090 | 0.1200 | 0.1349 | 0.2066 | 0.1513 | 0.1459 |
| E | 0.1645 | 0.0829 | 0.0967 | 0.0855 | 0.1240 | 0.1447 | 0.1164 |
| F | 0.1247 | 0.1019 | 0.0870 | 0.0960 | 0.0826 | 0.0987 | 0.0985 |

**Table 5** Normalized pairwise matrix

For each row, there is a total and for each column, there is a column. This will be divided by the total in each column. This was done for the whole table. From here, the researcher progressed to obtaining the criteria weight (Equation (2)), where the values of each row are summed and divided by the number of parameters (Table 5). This was the procedure followed to obtain the criteria weight. Now the researcher adds the criterion weight as the last column of Table 5. The weighted sum was then obtained but the consistency index was first evaluated (Table 6).

| | A | B | C | D | E | F | Weighted sum (WS) |
|---|---|---|---|---|---|---|---|
| A | 0.2696 | 0.3494 | 0.3147 | 0.2627 | 0.2095 | 0.2101 | 1.6161 |
| B | 0.1558 | 0.1807 | 0.2518 | 0.2140 | 0.1241 | 0.1707 | 1.0972 |
| C | 0.2037 | 0.0683 | 0.1888 | 0.2627 | 0.2172 | 0.2232 | 1.1640 |
| D | 0.1738 | 0.0924 | 0.1301 | 0.1459 | 0.1940 | 0.1510 | 0.8871 |
| E | 0.1857 | 0.0703 | 0.1049 | 0.0924 | 0.1164 | 0.1444 | 0.7142 |
| F | 0.1408 | 0.0864 | 0.0944 | 0.1038 | 0.0776 | 0.0985 | 0.6014 |

**Table 6** Weighted sum computation

The consistency index was obtained by multiplying each of the values with the original parameter ranking. Then the rows were summed to obtain the unexploited sum. Then the weighted sum was brought side by side with the signal-to-noise ratio, forming a table of two-column (Table 7).

| Labels | Weighted sum (WS) | $S/N=-10Log(1/n)\sum Y_i^2$ |
|---|---|---|
| 1 | 1.6161 (0.2658) | -34.8116 |
| 2 | 1.0972 (0.1805) | -34.8278 |
| 3 | 1.1640 (0.1914) | -34.8534 |
| 4 | 0.8871 (0.1459) | -37.9202 |
| 5 | 0.7142 (0.1175) | -37.9281 |
| 6 | 0.6014 (0.0989) | -37.9407 |
| 7 | - | -40.6301 |
| 8 | - | -40.6343 |
| 9 | - | -40.6411 |
| 10 | - | -38.1553 |
| 11 | - | -38.1664 |
| 12 | - | -38.1553 |
| 13 | - | -40.6281 |
| 14 | - | -40.6343 |
| 15 | - | -40.6281 |
| 16 | - | -35.8237 |
| 17 | - | -35.8426 |
| 18 | - | -35.8237 |
| 19 | - | -40.7577 |
| 20 | - | -40.7511 |
| 21 | - | -40.7557 |

**Table 7** Product of weighted sum and signal to noise ratios

| Labels | Weighted sum (WS) | S/N=-10Log(1/n)∑$Y_i^2$ |
|---|---|---|
| 22 | - | -36.2041 |
| 23 | - | -36.1854 |
| 24 | - | -36.1986 |
| 25 | - | -38.5061 |
| 26 | - | -38.4950 |
| 27 | - | -38.5028 |

**Table 7** (cont'd). Product of weighted sum and signal to noise ratios

One of the columns (left) is the weighted sum while the other column by the right is the signal-to-noise ratio data. It is input and to obtain a unified weighted by summing the total of the weighted sum and dividing by each of the values to obtain the weighted sum that is indicated in the bracket in front of the original weighted sum shown and a unified weighted sum in the branched. The next thing is to bring up the response table from the Taguchi method, which was the work done earlier (Table 8).

| AHP unified weight | 0.2658 | 0.1805 | 0.1914 | 0.1459 | 0.1175 | 0.0989 |
|---|---|---|---|---|---|---|
| Level | A | B | C | D | E | F |
| Level 1 | -37.7986 | -37.9149 | -35.6190 | -37.9875 | -38.1596 | -38.1556 |
| Level 2 | -38.2064 | -38.2520 | -38.1967 | -38.1715 | -38.1628 | -38.1616 |
| Level 3 | -38.4840 | -38.3221 | -40.6734 | -38.3301 | -38.1666 | -38.1718 |

**Table 8** Computation format for the response table for the work done on Taguchi with AHP unified weight

Thus, the response table for the work done was introduced on the Taguchi method. The next step is to multiply the unified weighted sum with the response table so that there could be the emergence of a table termed a unified AHP-Taguchi response table (Table 9).

| Level | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | -10.0469 | -6.8421 | -6.8191 | -5.5428 | -4.4824 | -3.7743 |
| 2 | -10.1553 | -6.9029 | -7.31259 | -5.5696 | -4.4828 | -3.7749 |
| 3 | -10.2291 | -6.9156 | -7.78675 | -5.5928 | -4.4832 | -3.7759 |
| Delta | 0.1822 | 0.0735 | 0.9676 | 0.0500 | 0.0008 | 0.0016 |
| Ranking | 2nd | 3rd | 1st | 4th | 6th | 5th |

**Table 9** AHP-Taguchi response table

Then each of the terms at each of the levels was multiplied with the AHP weights for each row of the parameter. From here, the researchers generated the optimal parametric setting for AHP-Taguchi analysis. From the table generated during the joint analysis performed between AHP and Taguchi principle, we can proceed with our discussion of the result as follows. The optimal parametric settings for the work done is $A_1B_1C_1D_1E_1F_1$ which is interpreted as 106units for a pulse on time, 40units for pulse off time, and 70units for Pulse Current, 20unit for Gap Voltage, 4units for Wire Feed and 4units for Wire Tension. Furthermore, the delta values for pulse on-time, pulse off-time, pulse current, gap voltage, wire feed and wire tension for the work done are 0.1822, 0.0735, 0.9676, 0.0500, 0.0008, and 0.0016 respectively. Also, the ranks of the factors after the AHP-Taguchi analysis are as follows: C (pulse current) ranked 1st (first), A (pulse on-time) ranked 2nd (second), B (pulse off-time) ranked 3rd (third), D (gap voltage) ranked 4th (fourth), F (wire tension) ranked 5th (fifth) and E (wire feed) ranked 6th (sixth).

Notice that in the classical Taguchi method where the optimal parametric settings are the final output of the optimization method, the mechanism for attaining ranking after establishing the optimal parametric setting is dependent on the delta values, which are the differences between the lowest and highest within the column for each parameter. These delta values reveal how strong each parameter is towards the attainment of the goal of the process. Hence, delta value evaluation is fundamental to the evaluations done in the present article since the proposed methods are based on the Taguchi method.

## 4.2 Comparing the proposed methods with the Taguchi method

Tables 10 and 11a,b, and c show the response tables for the AHP-Taguchi-Pareto and AHP-Taguchi-ABC methods while Table 12 shows the Taguchi response table for the problem, aimed at verifying the correctness of the proposed methods. The details of how to obtain Tables 10 to 12 have been explained in the methodology aspect of this work and further details could be obtained from the literature.

| Level | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | -10.4413 | -7.1204 | -6.9296 | -5.7731 | -4.5778 | -3.8545 |
| 2 | -10.4711 | -6.9030 | -7.3126 | -5.7405 | -4.5777 | -3.8551 |
| 3 | -10.2291 | -7.1406 | -7.7868 | -5.5928 | -4.5782 | -3.8557 |
| Delta | 0.2420 | 0.2375 | 0.8572 | 0.1803 | 0.0005 | 0.0012 |
| Ranking | 2nd | 3rd | 1st | 4th | 6th | 5th |

**Table 10** AHP-Taguchi-Pareto Response Table

| Level | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | -10.8008 | -7.1204 | 0 | -5.7731 | -4.6675 | -3.9302 |
| 2 | -10.4711 | -7.3321 | -7.3382 | -5.9466 | -4.6676 | -3.9306 |
| 3 | -10.5331 | -7.1405 | -7.7868 | -5.7485 | -4.6677 | -3.9311 |
| Delta | 0.3298 | 0.2117 | 0.4486 | 0.1981 | 0.0001 | 0.0009 |
| Ranking | 2nd | 3rd | 1st | 4th | 6th | 5th |

**Table 11a** AHP- Taguchi ABC response table (Part A)

| Level | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | -10.0817 | 0 | -6.9296 | 0 | -4.3535 | -3.6652 |
| 2 | 0 | -6.6884 | -7.2615 | -5.5343 | -4.3529 | -3.6663 |
| 3 | -9.6209 | 0 | 0 | -5.2814 | -4.3544 | -3.6672 |
| Delta | 0.4608 | 0 | 0.33190 | 0.2530 | 0.0015 | 0.0019 |
| Ranking | 1st | 6th | 2nd | 3rd | 5th | 4th |

**Table 11b** AHP- Taguchi ABC response table (Part B)

| Level | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | -9.2581 | -6.2856 | -6.7639 | -5.0822 | -4.1486 | -3.4936 |
| 2 | -9.5236 | 0 | 0 | -5.2280 | -4.1507 | -3.4944 |
| 3 | 0 | -6.4659 | 0 | 0 | -4.1510 | -3.4966 |
| Delta | 0.2656 | 0.1803 | 0 | 0.1458 | 0.0025 | 0.0030 |
| Ranking | 1st | 2nd | 6th | 3rd | 5th | 4th |

**Table 11c** AHP- Taguchi ABC response table (Part C)

| Level | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | -37.7986 | -37.9149 | -35.6190 | -37.9875 | -38.1596 | -38.1556 |
| 2 | -38.2064 | -38.252 | -38.1967 | -38.1715 | -38.1628 | -38.1616 |
| 3 | -38.9898 | -38.3221 | -40.6734 | -38.6063 | -38.1666 | -38.1718 |
| Delta | 1.1912 | 0.4072 | 5.0544 | 0.6188 | 0.0070 | 0.0162 |
| Rank | 2nd | 4th | 1st | 3rd | 6th | 5th |

**Table 12** Taguchi response table

The optimal parametric settings for AHP-Taguchi-Pareto is $A_3B_3C_3D_1E_3F_3$ which is interpreted as 126 units for a pulse on time, 60 units for pulse off time, and 230 units for pulse current, 20 units for gap voltage, 8 units for wire feed and 12 units for wire tension. Furthermore, the delta values for pulse on-time, pulse off-time, pulse current, gap voltage, wire feed and wire tension for the work done are 0.2420, 0.2375, 0.8572, 0.1083, 0.0005, and 0.0012 respectively. Also, the ranks of the factors after the AHP-Taguchi analysis are as follows: C (pulse current) ranked 1st, A (pulse on-time) ranked 2nd, B (pulse off-time) ranked 3rd, D (gap voltage) ranked 4th, F (wire tension) ranked 5th and E (wire feed) ranked 6th. The optimal parametric settings for AHP-Taguchi-ABC (Part A) is $A_1B_2C_3D_2E_3F_3$ which is interpreted as 106 units for a pulse on time, 50 units for pulse off time, and 230 units for pulse current, 40 units for gap voltage, 8 units for wire feed and 12 units for wire tension.

Furthermore, the delta values for pulse on-time, pulse off-time, pulse current, gap voltage, wire feed and wire tension for the work done are 0.3298, 0.2117, 0.4486, 0.1981, 0.0001, and 0.0009 respectively. Also, the ranks of the factors after the AHP-Taguchi analysis are as follows: C (pulse current) ranked 1st, A (pulse on time) ranked 2nd, B (pulse off-time) ranked 3rd, D (gap voltage) ranked 4th, F (wire tension) ranked 5th and E (wire feed) ranked 6th. Furthermore, the order of ranking of parameters according to the Taguchi and AHP-Taguchi methods coincides with 4/6 parameters, equivalent to 66.7%. The ranking order of parameters according to the Taguchi and AHP-Taguchi-ABC Parts A, B and C coincide with 4/6 parameters, equivalent to 66.7% for the Taguchi-AHP-Taguchi-ABC Part A analysis. However, comparing Taguchi and Taguchi-ABC Parts B and C yield only 1/6, which is 16.7% in each respective case. Future studies may consider extending the present framework to incorporate aspect ratios and a comparison may also be made with Muniappan et al. [36] for a robust exercise.

Besides, the Taguchi method is the conventional method while the AHP-Taguchi-Pareto and AHP-Taguchi-ABC methods are the proposed method whose correctness is to be verified. Firstly, the AHP-Taguchi method is compared with the conventional Taguchi method by the ranks of parameters. It was found (see Tables 9 and 12) that the order of ranking according to the Taguchi and AHP-Taguchi method coincides with the following parameters: pulse on time (A), pulse current (C), wire feed (E), and wire tension (F). This means four parameters out of six agree, equivalent to 4/6, which is 66.7%. In comparing Tables 10 and 12, the order of ranking according to Taguchi and AHP-Taguchi-Pareto methods still coincides with the same four parameters as previously mentioned, maintaining a 4/6 equivalence of parameters, which is still 66.7%. To compare the Taguchi method and the AHP-Taguchi-ABC (Parts A, B and C), Tables 11a, 11b and 11c are compared with Table 12, the ranking order still coincides with the results obtained previously, which means that 66.7% of the parameters are in agreement of positions. This is for Part A of the AHP-Taguchi-ABC in comparison with the Taguchi method. For the Taguchi and AHP-Taguchi-ABC Part B comparison, only the gap voltages coincide in ranking for the two methods, showing only a 16.7% agreement. Furthermore, when the Taguchi and AHP-Taguchi-ABC Part C are compared, it was noticed that still, only 16.7% of the parameters coincide, which is also for the gap voltage parameter.

### 4.3 Advantages of the proposed method

This article develops a bi-attribute method that selects the wire EDM parameters for processing the AZ91 magnesium alloys based on their importance and concurrently optimises them to reduce production costs while ensuring efficiency. The approach is named the analytic hierarchy process with Taguchi analysis to take full advantage of a proven method in which several parameters are accommodated in the analysis despite the complication and the multiple conflicting criteria of the wire EDM parameters. The method presents an easy-to-use framework where the AHP module generates effective criteria weights which are further used in an optimization framework involving the Taguchi analysis. Since multiple resources must be distributed before and during the wire EDM process, there exists the problem of what quantity of resources to distribute to each workstation and at what time? Therefore, in response to this concern, this article enhances decision-making in the distribution of the resources by initiating the idea of analyzing, and selecting the wire EDM process parameters during the machining of the AZ91 magnesium alloy to evolve weights to be deployed in the response table for further analysis. The determined weights are then merged with the signal-to-noise ratios, which assists the method to identify the optimal parametric setting through a scrutinisation process where the delta values and ranks of the parameters are established to obtain usable results for planning purposes.

It could be observed that the optimal parametric setting obtained using the AHP-Taguchi method is better than the one given by the Taguchi method. The reason is that the former introduces a prioritisation scheme effective to decide on the most important parameters in the wire EDM process and subsequently optimises the parameters for enhanced quantitative and qualitative information decision-making in the wire EDM process of AZ91 magnesium alloys. To further explain this, consider the limited resources for deployment to wire EDM sources. As parameters that should be given more attention are known for prioritisation, more of the resources are purchased and deployed to relevant parameters than those requiring less attention. A balance would still be maintained by the process engineer such that the efficiency and effectiveness of the wire EDM system are still being maintained.

## 5. Conclusion

In this article, the AHP method is integrated with the Taguchi, Taguchi-Pareto and Taguchi-ABC methods, two of these methods were used to prioritise and concurrently optimise the EDM parameters. The AHP weights were multiplied against the Taguchi table generated from the experimental data of Muniappan et al. [12] in all cases. This aided the researchers to develop the optimal parametric settings. The details of the optimal parametric settings are as follows. For the AHP-Taguchi method, the first element, A, which is the pulse on time, specifically yielded $A_2$. Then B, which pulse off time was obtained as $B_1$. Then C, which is current is $C_1$. Also for the D, which is the gap voltage is $D_1$. Furthermore, for the E, which is the wire tension is given as $E_1$. Then for F, there is $F_4$ where the optimal parametric setting is summarized as $A_2B_1C_1D_1E_1F_1$. Then, the interpretation is as follows. As $A_2$ was obtained for the pulse on time, the initial factor-level table given by Muniappan et al. [12] was read to understand what $A_2$ means from the table. Thus, from the analysis carried out, it was discovered that $A_2$ which represents the pulse on time has the value 116-ampere table. The optimal parametric setting is interpreted as 116 microseconds of pulse on time, then $B_1$ as 40 microseconds of pulse off time. Others are $C_1$ as 70 amperes of pulse current than 20 volts of gap voltage, like $D_1$. Then, there is 4mm of wire feed as $E_1$ and 4mm of wire tension as $F_1$. Furthermore, the delta values for the pulse on time, pulse off time, current gap voltage, wire feed and wire tension are 0.1822, 0.0735, 0.9676, 0.0500, 0.0008 and 0.0002, respectively.

For the ranking, the ranks of the factors after coupling the AHP with the Taguchi analysis are as follows. Current is ranked first then the second position is the pulse on time while the third position is the pulse off time. Furthermore, the fourth position is the gap voltage. The fifth position is the wire tension and then the sixth position is the wire feed. The optimal parametric settings for AHP-Taguchi-Pareto is $A_3B_3C_3D_1E_3F_3$ which is interpreted as 126 units for a pulse on time, 60 units for pulse off time, and 230 units for pulse current, 20 units for gap voltage, 8 units for wire feed and 12 units for wire tension. Furthermore, the delta values for pulse on-time, pulse off-time, pulse current, gap voltage, wire feed and wire tension for the work done are 0.2420, 0.2375, 0.8572, 0.1083, 0.0005, and 0.0012 respectively. Also, the ranks of the factors after the AHP-Taguchi analysis are as follows: C (pulse current) ranked 1st, A (pulse on-time) ranked 2nd, B (pulse off-time) ranked 3rd, D (gap voltage) ranked 4th, F (wire tension) ranked 5th and E (wire feed) ranked 6th.

The optimal parametric settings for AHP-Taguchi-ABC (Part A) is $A_1B_2C_3D_2E_3F_3$ which is interpreted as 106 units for a pulse on time, 50 units for pulse off time, and 230 units for pulse current, 40 units for gap voltage, 8 units for wire feed and 12 units for wire tension. Furthermore, the delta values for pulse on-time, pulse off-time, pulse current, gap voltage, wire feed and wire tension for the work done are 0.3298, 0.2117, 0.4486, 0.1981, 0.0001, and 0.0009 respectively. Also, the ranks of the factors after the AHP-Taguchi analysis are as follows: C (pulse current) ranked 1st, A (pulse on time) ranked 2nd, B (pulse off-time) ranked 3rd, D (gap voltage) ranked 4th, F (wire tension) ranked 5th and E (wire feed) ranked 6th.

Furthermore, the order of ranking of parameters according to the Taguchi and AHP-Taguchi methods coincides with 4/6 parameters, equivalent to 66.7%. The ranking order of parameters according to the Taguchi and AHP-Taguchi-ABC Parts A, B and C coincide with 4/6 parameters, equivalent to 66.7% for the Taguchi-AHP-Taguchi-ABC Part A analysis. However, comparing Taguchi and Taguchi-ABC Parts B and C yield only 1/6, which is 16.7% in each respective case. Future studies may consider extending the present framework to incorporate aspect ratios and a comparison may also be made with Muniappan et al. [36] for a robust exercise.

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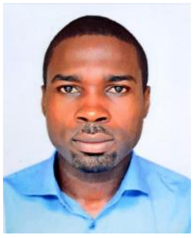
## Biographies



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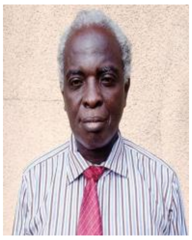

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Appendix

The questionnaire was administered to determine the importance of different criteria in an Electric discharge machining (EDM) process over another.

**Definition of table**

0 = No Importance
1 = Equal Importance
2 = Moderate Importance
3 = Strong Importance

Please tick as appropriate

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

**EXAMPLE**

How would you rate the importance of pulse on time over pulse off time?

**Descending** **Ascending**

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

1. How would you rate the importance of pulse on time over pulse off time?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

2. How would you rate the importance of pulse on time over pulse current?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

3. How would you rate the importance of pulse on time over gap voltage?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

4. How would you rate the importance of pulse on time over wire feed?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

5. How would you rate the importance of pulse on time over wire tension?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

6. How would you rate the importance of pulse off time over pulse current?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

7. How would you rate the importance of pulse off time over gap voltage?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

8. How would you rate the importance of pulse off time over wire feed?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

9. How would you rate the importance of pulse off time over wire tension?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

10. How would you rate the importance of pulse current over gap voltage?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

11. How would you rate the importance of pulse current over wire feed?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

12. How would you rate the importance of pulse current over wire tension?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

13. How would you rate the importance of gap voltage over wire feed?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

14. How would you rate the importance of gap voltage time over wire tension?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |

15. How would you rate the importance of wire feed over wire tension?

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 0 | 1 | 2 | 3 |