Optimization of Wire Electrical Discharge Machining Process Parameters in AZ91 Magnesium Alloy Using Taguchi-Based Fuzzy Analytic Hierarchy Process (TFAHP) Method

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Abstract. *In the electrical discharge machining process optimization domain, a dominant approach to optimization is the Taguchi method, which is favoured for its simplicity and low-cost implementation requirements. However, the results obtained from the Taguchi method have been criticized as susceptible to errors and wrong decisions since it is based on crisp numerical values. Unfortunately, the impact of such wrong decisions cannot be tolerated as it has a chain effect on the non-financial aspects of the organization's practice such as loss of goodwill. To reverse this issue, research is urgently desired. This article aims to optimize and fuzzifier the electrical discharge machining process parameters using the Taguchi method and the fuzzy analytic hierarchy process method. This article introduces a capturing mechanism of uncertainty and imprecision aspects into the Taguchi method and the Taguchi method has been modified as a new method termed the Taguchi method fuzzy analytic hierarchy process method (T-FAHP). The T-FAHP converts the crisp numerical values into fuzzy numbers which were optimized. The optimal parametric settings and rankings of factors were determined. The optimal parametric settings, delta values, ranks and comparison results were pursued. It was found that the optimal parametric setting did not change from those of the T-AHP results. It yielded* $A_1B_1C_1D_1E_1F_1$ *interpreted as pulse on time (160units), pulse off time (40units), pulse current (70 units), gap voltage (20 units), wire feed (4 units) and wire tension (4 units). The ranks were led by pulse current and last by wire feed. The ranking occurred in a different order but the first and the last positions were assigned to pulse current and wire feed, respectively. For the delta values, considering Taguchi AHP against when using the Taguchi-fuzzy analytical hierarchy process, we had a reduction of 16.49% for the pulse current, an increase of 28.57%, for the pulse off time, a decrease of 55.56%, for the gap voltage, no changes, for wire feed, no changes, for wire tension, an increase of roughly 10%. The results obtained from this study are suitable for use by process engineers in the machining industry for cost-effective machining decisions.*

Keywords:
optimization, EDM process, Taguchi method, fuzzy AHP

1. Introduction

These days, there is an increasing competitiveness among the automobile and aerospace industries globally. For instance, the competitiveness of the china's automobile industry had been recognized decades ago [1]. Mexico's automobile part supplier's competitiveness was discussed in Valdez de la Rosa et al. [2]. Furthermore, the global relevance of France and Korea in the automobile industry's competitiveness was discussed by Lee [3]. However, the competitiveness is heightened by customers' demand for greater details of components and additional features such that the utility of the components is increased. Still, in the expanded scope of global competitiveness in the automobile industry, Doner et al. [4] demonstrated competitiveness in the auto parts industry within the Asian context. Moreover, apart from the automobile industries, competitiveness has been extended to the aerospace industry with examples from the UK aerospace industry [5].

Given the competition, rival companies strive to attain previously unattainable heights in material processing using novel technologies such as electrical discharge machining. Many parts of the automobiles such as engines and bodies are conductive materials containing super alloys, aluminium, steel, alloys, titanium and brass, which can be cut using the wire EDM approach. Thus, automobile products achieve an improved quality of life for commuters by processing their parts using the EDM process to yield comfort, increased mobility and safety. For the aerospace industry, components of flight vehicles such as aircraft, rockets and missiles have electrically conductive parts such as gears, aircraft doors, and airframe structures. Consequently, a rapid transportation network is delivered to customers with the advantages of economic growth, and international trade facilitation, among others.

From the discussion above, the wire electrical discharge machining process (WEDM) occupies a central position in the volumetric production of components across the automobile and aerospace industries. Today, several studies have been conducted on WEDM largely because the process is well suited for improving die corner accuracy [6], trim cutting [7], and micro rod production [8]. Other studies on wire EDM have been conducted based on the merits of materials for achieving the desired purpose of excellent performance during usage [9]. Thus, the following materials have been explored in wire EDM processes. These are the hybrid nano-SiC and Nano-ZrO_2 reinforced aluminium [10].

Notwithstanding, as products are created from the electrical discharge machining process, the evaluation of the progress of the process is still commonly done using crisp numerical values [11],[12],[13],[14]. However, uncertainty and imprecision prevail while processing and recording the progress of materials using the EDM system [15],[16],[17]. In this work, the Taguchi method is applied and the results are used to further the two main aspects involved in the present study. Notice that only the extraction of results from a previous study is done as there is no need to duplicate the process of the Taguchi method using the same data in this work [18]. The two aspects of the further study are: first, the experimental data is analyzed from the specific reference source to obtain the fuzzy analytic hierarchy results. In the second aspect, questionnaires are administered and analyzed to obtain experts' opinions upon which the fuzzy decision judgments are made. For the experimental aspect, equipment calibration is involved and data collection by the human elements is also included. These aspects generate uncertainty and imprecision in the data gathered and analyzed. Also, the questionnaire administration and sometimes analysis may introduce uncertainty and imprecision. It thus becomes compelling to reduce and possibly eliminate these unwarranted negative impacts on the results obtained from an EDM analysis. The argument made in this article is that errors from questionnaire administration, equipment calibration and process operation may obstruct the accuracy of the results. Hence, decisions made based on these data may be wrong. Consequently, the objective of the present article is to apply the fuzzy analytic hierarchy process to the Taguchi method for the parameters of the electrical discharge machining while using a material. To achieve the application of the fuzzy analytic hierarchy process, questionnaires are developed and administered based on the experimental data obtained from the literature.

Moreover, some studies have reported that properly prioritized and ranked process parameters and the effective implementation of their results could influence noticeable improvements in the performance of such processes [19]. Thus, from the previous discussion and analysis as well as comments given above, the following are known. The Taguchi method exhibits several benefits and the key benefits include the possibility of evaluating several electrical discharge machining parameters and the development of robust experimental designs that save time and cost [20],[21],[22],[23]. The AHP method has the advantage of tackling both the qualitative and quantitative aspects of the wire electric discharge machining parametric evaluation and decision process [18],[19]. The fuzzy method has the advantage of requiring no precise inputs for evaluation [24].

In the electrical discharge machining process, the Taguchi method has been implemented in several studies such as Barman et al. [9], Singh and Pradhan [14], Mohamed and Lenin [25] and George et al. [26]. Besides, the AHP method has also been used in the EDM process research domain, including Arora et al. [19]. Also, the fuzzy method was applied to the parametric evaluation of the EDM process as evidenced by Sahu and Srivastava [16] and Zhou et al. [17]. Interestingly, scholars have integrated one or more of the Taguchi method, the AHP method and the fuzzy method with applications to the EDM process as shown in Nayak and Mahapatra [27] where the Taguchi method was integrated with the AHP method. From the previous discussion, the advantages of the Taguchi method, AHP method and fuzzy method had been derived in studies that applied each of these methods alone and some that combined the Taguchi method with the AHP method. However, the combination of the Taguchi method with two methods of AHP and fuzzy had not been implemented in any studies associated with the wire electrical discharge machining in general as well as using the AZ91 magnesium alloy in particular [15],[23]. This gap will be explored in the present article. In particular, experimental data from Muniappan et al. [28] will be utilized to test and verify this robust method of Taguchi-based fuzzy AHP method using the AZ91 magnesium alloy as the work material. Furthermore, there is a plethora of other performance enhancement techniques that have been proposed for the electrical discharge machining (EDM) process in the last couple of years. These tools include the Taguchi-Pareto method and the Taguchi-ABC methods [11]. Others are fuzzy logic [24] and utility concept [21].

Still, other tools include ANOVA principles and utility index [27], utility concept and quantum behaved particle swarm optimization [29], artificial neural network, bat algorithm, maximum deviation concept [30], harmony search procedure, regression analysis and TOPSIS [31]. The Taguchi method was initiated to reduce the experimental cost of the electrical discharge machining problem. The Taguchi-Pareto and Taguchi-ABC methods were installed in EDM systems to concurrently optimise process parameters and produce prioritized parameters with which the focus of attention could be made. This entails the prudent distribution of resources available to the EDM system. The fuzzy logic was proposed in the EDM domain to attain a balance between the input parameters and the output parameters using a set of fuzzy rules based on the "IF-THEN" language. The utility function was introduced into the EDM arena to complement the weakness of the Taguchi method. Furthermore, the analytic hierarchy process was installed in the EDM system to identify preferences of factors on Saaty's importance scale. Accordingly, Raji and Oke [11] deployed the Taguchi and analytic hierarchy process in the machining of an aluminium alloy 6061. The same authors demonstrated the utility of Taguchi Pareto and Taguchi-ABC in maintaining an efficient machining system for the AA6061 material for the EDM process [11]. Furthermore, Chakraborty and Das [24] promoted the use of fuzzy logic based on IF-THEN rules to capture the imprecision and uncertainty in the electrical discharge machining process while demonstrating the practical relevance of the method using experimental data. The idea of utility was introduced by Kandpal et al. [21] when the weakness of the Taguchi method was complemented with the innovative tool of the utility concept. All these tools provided useful but fruitful results for the efficient running of the EDM process. However, the EDM process is a known nontraditional machining approach that ignores the properties of the materials being processed and still delivers efficient results. The EDM process uses di-electric fluids, which have radically changed over the years to expand the capability of the EDM system. Often, the EDM system is based on certain output considerations common among them are the material removal rate and surface roughness. It also has diverse input parameters but some noticeable ones are the discharge current, pulse on time pulse off time, among others.

A summary of other important studies related to the present work follows. Nayak and Mahapatra [27] established the best parametric values for the taper-cutting activity in the wire EDM process. The mathematical framework of multiple response optimization was used to explain the data which focused on responses of surface roughness, angular error and cutting speed while the corresponding process parameters interacted with namely, wire speed, pulse duration, wire tension, part thickness, discharge current and taper angle. The approach used is a combination of the Taguchi method, ANOVA principles, utility index and analytic hierarchy process. Nayak et al. [31] used a multiple response optimization method to establish the best parametric values in taper cutting operation while using the AISI D2 tool steel in a WEDM process. The methods used are the harmonic search procedure, regression analysis, TOPSIS and Taguchi's orthogonal array. The feasibility of the approach was confirmed with experimental data obtained from a CVC WEDM machine. Nayak and Mahapatra [30] established an optimization procedure based on the maximum deviation concept and artificial neural network method to process cryo-treated super alloy (Inconel 718) using the wire EDM procedure. Then bat algorithm was applied to the results. It was declared that the suggested method yielded satisfactory results.

Considering the techniques elaborated in the previous paragraphs the performance means uses are commonly approached from the crisp numerical values' perspective. For instance, all through the development of the Taguchi method, the crisp numerical values approach has been followed. Also, the factor-level appraisal, introduction of the signal-to-noise quotient, and summarization of the Taguchi method as the response table follow the crisp numerical value approach. Besides, several additional approaches such as the analytic hierarchy process do not have the uncertainty and imprecision component as they still visualize from the crisp numerical value perspective. Instead of contemplating on the optimistic, pessimistic and most likely aspects of a value, all the methods mentioned in the previous paragraphs still focus on only the most likely aspect of the value. However, the fuzzy analytic hierarchy process (FAHP) method proposed in this article for the electrical discharge machining process optimization assists the process engineers in arriving at the best (optimal) parametric setting for the factors in the selection process while following the Taguchi methodical route. The fuzzy analytic hierarchy method based on the geometric means principles has been deployed on the Taguchi method where it aids in the development of the factor level table, evaluation of the signal-to-noise ratios and finally the response table. Thus, the argument made in the present article is that to introduce the uncertainty and imprecision aspects into the Taguchi method, the Taguchi method has been modified as a new method termed the Taguchi method-fuzzy analytic hierarchy process method, shortened as the T-FAHP method. The T-FAHP method introduces the uncertainty and imprecision into the stages of the Taguchi method. In this approach, crisp numerical values have been converted into fuzzy numbers where three components of the number in a matrix form are established.

Consequently, as the need to bridge this gap has matured, this study aims to optimize, prioritize and rank the wire EDM process parameters in the conditions of uncertainty and imprecision of the parametric evaluation and development using the Taguchi-based fuzzy analytic hierarchy process using experimental data from Muniappan et al. [28] for an experimentally conducted process of the wire electrical discharge machining. Thus, the specific objectives of the work are to first establish the concurrent optimization and prioritization of the parameters of the wire EDM process for the AZ91 magnesium alloy using the Taguchi-based fuzzy analytical hierarchy process. Secondly, the relative weights of the fuzzy-oriented method are to be determined. Thirdly, the normalized weights of the parameters (criteria) for each parametric category are to be determined.

In this study, the domain of the fuzzy AHP method is the decision-making research area. But within this area, several important tools are available such as net present value, influence diagram approach, conjoint analysis, games theory, paired competition analysis, heuristics, multi-voting, affinity diagrams, linear programming, cost-benefit analysis, decision analysis and fuzzy AHP method. However, the present authors embarked on the use of the fuzzy AHP method to couple the Taguchi method and not another decision-making tool because decision-makers often develop more confidence to provide interval judgements than firm value judgements. It implies that the decision-makers have the opportunity to create more confident data and create sound decisions.

2. Background

2.1 Original experimental data

The wire electrical discharge machining data considered in this study was experimented with by Muniappan et al. [28]. It considered the following parameters, Pulse on time, pulse off time, gap voltage, wire feed, wire tension and pulse current. Furthermore, after producing the fabricated samples through the stir-casting process, Muniappan et al. [28] deployed the MOORA multicriteria to evaluate the parameters according to their order of importance. While MOORA multicriteria is an important and novel tool for parametric optimization, the present authors argue that prioritizing the influence of the wire electrical discharge machining process parameters on the system is not sufficient as there is the possibility of having the risk of sub-optional values in the evaluation. This, to overcome this problem, the present study has proposed a combination of the Taguchi method and the AHP method to solve the problem, Yet, it was further thought that there exists imprecision and uncertainty, Which had been ignored in previous computations and puts the evaluation of the system at risk of obtaining wrong results for wrong decisions. But to overcome this challenge, the proposed method is modified to include the fuzzy system, called the Taguchi-fuzzy-AHP method to establish the parametric values of the wire electrical discharge machining process while fabricating the AZ91 magnesium alloy.

2.2 Producing AZ91 magnesium alloy using stir casting set-up

In this article, the composite named AZ91 magnesium alloy is produced using the stir casting set-up. Magnesium alloy is a combination of magnesium (special gravity of 1.74 and it is (the highest structural metal in widespread usage). To achieve the stir-casting process of magnesium alloy, magnesium is alloyed (mixed) with diverse arrangements with alloying elements such as zinc, silicon, aluminium and manganese as well as rare earth. It also contains other elements that are technically named impurities with the upper bound of what these impurities could be in percentage. Being extremely useful in the industry, the demand for magnesium alloys for different slightly varying conditions has forced the production of magnesium alloys with different nomenclatures such as AZ91, AZ63, QE22 and WE43 among others. However, the AZ91 nomenclature is of interest to the present researchers. These nomenclatures are founded by the American Society of Testing and Materials (ASTM) where the designations express both chemical compositors and tempers of the particular magnesium alloy being considered. The designation AZ91 has AZ as the first two capital letters representing the first into major alloying elements with a decreasing percentage range from A to Z, The numeral 91 indicates the rounded-up percentages to whole numbers. Now, the stir-casting set-up is discussed.

The stir casting set-up contains parts, including a stirrer, furnace rotor, crucible and some materials such as liquid metal and reinforcement. The stirrer nod and stirrer impellers are parts of the stirrer. However, the motion of the stirrer rod is propelled by a motor. The design of the stirrer in the stir casting set-up is such that it forms a physics phenomenon called a vortex line that swirls amount. This action is stimulated by velocity differentials of what surrounds the line. The vortex is formed when the reinforcing materials (magnesium) and molten metals are mixed. The stir casting set-up consists of a stirring rod that creates contacts, which assists in counteracting the adhesion between the inner sides of the crucible and parts of the lower surface of the crucible and the liquid being stirred. The system also contains an impeller. The stirring rod has a connection that helps to operate the mechanical stirrer. There is a functioning feeder that supplies the reinforcement material to the molten magnesium alloy. Attached to the stir casting set-up are the bottom pouring furnaces that help to pour the melt directly into the mound while reducing the manual task of pouring, which may be challenging to achieve. If the bottom pouring furnaces are not considered then the process engineer may be saddled with the task of lifting the melt and pouring it into the mound. But the bottom pouring furnaces eliminate this hazardous task by working through a remote switch. The pouring is quickly done to eliminate the sticking of particles to the walls of the crucible.

The procedure for producing AZ91 magnesium alloy entails putting the magnesium in the crucible that is surrounded by the furnace. The magnesium undergoes melting. Reinforcements which could be zinc, aluminium or manganese are added to the molten magnesium, in this instance, a stirrer that is propelled by the electric motor and operating at a speed range between 200 rpm and 400 rpm moves the molten metal in swirls while the temperature of the molten magnesium is above 600ºC. At stirring, the added reinforcements mix up with the molten metal magnesium. It is important to consider some parameters to prevent the reinforcements from settling at the bottom of the crucible. These parameters that promote proper mixing of the molten metal and the reinforcement are the stirring speed, stirring temperature and stirring time, the stirring time may be set at 10 mins at 100 rpm. A major factor also influencing the quality of the solidified material is the pouring height during the process. If the reinforcement (zinc or aluminium) is poured into the melt (magnesium) at a very high altitude, there are doubts that the melt and reinforcement will properly mix, this means that pouring should be relatively close in height to the height of the furnace above the ground.

2.3 Significance of the study

The first significance of this research is to offer a platform for process engineers and managers and the operators of the wire electrical discharge machining while processing the AZ91 magnesium alloy to review their policies involving some of the following. The choice of dielectric fluids may be based on the parametric values when different fluid types such as lubricating oil, transformer oil, air, kerosene and paraffin oil, among others, are tested. A second issue is the decision on the choice of an electrode material, which could be guided by the electrode's conductivity and the resistance of the material to erosion. In the above instances of the choice of dielectric fluids and electrode materials, there is no guidance being followed in practice and the choice is arbitrary. This results in huge expenditure for the wire EDM system and it drains the wealth of the machining workshop, which could have been conserved for sustainable machining practices. Furthermore, the second significance of the present research is that there are limited studies on the combined optimisation and prioritization in the wire electrical discharge machining process where the AZ91 magnesium alloy has been used. In these studies, only in recent times has the Taguchi method, which permits qualitative and quantitative interaction with the data been combined with the robust analytic hierarchy process that utilizes an expert's opinion. However, expanding the framework to track imprecision and uncertainty using the fuzzy system makes this study important to the wire electrical discharge machining system and the machining community as a whole. Thirdly, this study predicts the kerf width, which measures the width of the AZ91 magnesium alloy removed during the cutting process. Kerf width provides an idea of how precise cuts are accomplished. The research also evaluates the cutting speed that shows the rotational speed of the AZ91 magnesium material or the cutting tool. But the kerf width and cutting speed are global representatives of the wire EDM responses and hence predict the performance of the wire EDM process as a whole thereby providing the process engineers information on the extent of accomplishment of machining goals. The fourth significance of this research is that resulting from the survey of the literature, the present authors established a method that has the potential to enhance wire EDM process performance through parametric selection. From a holistic perspective, the present research offers Evidence to readdress the performance enhancement problem in the wire EDM process. Performance improvement is an alarming issue in the machining industry with the consequential effect of affecting production and the well-being of operators.

3. Method

First, we considered the parameters from the table, which is referenced by Muniappan et al. [28]. The parameters are pulse on time, pulse off time, pulse current, gap voltage, wire feed and wire tension. Then we brought out our table and also used symbols to represent items which are A, B, C, D, E and F for pulse on time, pulse off time, pulse current, gap voltage, wire feed and wire tension. The values in the table are referenced from Muniappan et al. [28]. We considered using the Taguchi method first. Here, we had to first introduce the Minitab software to display and distribute the parameters being worked upon in an orthogonal array using the L27 orthogonal array. Then the authors produced the signal-to-noise ratios considering the lesser the better option. We generated a table in which we inserted the figures based on the formula for the lesser the better option of signal-to-noise ratio. After achieving this result, the authors proceeded to generate the signal-to-noise ratio table. Since it is known that further from this point the response table will be generated, it was generated and kept aside. Then the authors proceeded to fuzzy analytical hierarchy processed with the geometric mean method option. It should be noted that these previous steps were implemented previously in Ikedue and Oke [18] and the data results will not be repeated here. The procedure is mentioned here only for an adequate flow to obtain the results of the TFAHP. Thus, researchers interested in verifying the results omitted here are expected to read Ikedue and Oke [18]. This work is an extension of the mentioned article. However, the major difference between the two articles is the addition of the fuzzy analytic hierarchy process to the Taguchi method to replace only the analytic hierarchy process added to the Taguchi method in the previous study. The extension starts from this part, which introduces the fuzzy analytical hierarchy process to the work, merging it with the Taguchi-based analysis.

The second part introduces the fuzzy analytical hierarchy process. Here, some explanations of how the researchers gathered the data for the fuzzy component of the Taguchi-fuzzy analytic hierarchy process method are provided. This was aided by developing and administering questionnaires tailored to capturing the experts' opinions on the subject of interest. Data was gathered from selected similar inputs of different professionals and used for this particular work. Doing this, the researchers were able to gather data from questionnaires that were given out to various experts, to express their views on the order of importance of these parameters. From that, certain information for decision-making was gathered. In considering fuzzy analytical hierarchy, the first part is for the researcher to determine the fuzzy scales. For this, the researchers had 5 items initially, we had 0, which means no importance, 1 means equal importance, 2 means moderate importance, and 3 means strong importance. However, for fuzzy discussion, 4 is introduced, which is very strong in importance. This is to have a balance and for the focal point.

Concerning the questionnaire, to bring out the fuzzy values, the researchers embarked on obtaining the average values of the various inputs that are similar. From the research, it is noted that it is possible to analyze every questionnaire generated. Because there were some questionnaires whose inputs were similar, those were gathered from the field it is possible to have the same title but different work altogether. To further explain, because there are some figures which some experts had filled, it may not be possible to analyze those questionnaires because they included zero, which is of no importance. "In using zero, it automatically nullifies the work and the researcher is not able to perform analysis because zero is not a value that could be used for transformation purposes, i.e. a null value. Notice that this null value nullifies anything you are multiplying it with. This is because at a point in time, in the analysis, the researcher had to multiply some certain data to be able to obtain particular results. So, for this work, the authors skipped those questionnaire items that have included zero. Then the researchers developed a table for each parameter. This is referred to as a level-wise-parameter-wise table for the fuzzy analytic process.

3.1 Taguchi method and fuzzy analytic hierarchy process (FAHP) method

To apply the TFAHP method, the following consists of a detailed explanation of how the method was applied commencing with the Taguchi methodical implementation. Hence, the following are the steps taken to implement the TFAHP method:

Step 1: Promote the idea of factor level development to evolve the orthogonal array from the problem formulation.

Step 2: Interpret the orthogonal array and link it with the signal-to-ratio development indices.

Step 3: Identify and use any or all of these signal-to-noise indices of smaller-is-better larger-is-better and nominal-the-best to compute the signal-to-noise ratios for each experimental trial.

Step 4: Obtain the averages of these signal-to-noise ratios and introduce the response table to organize these ratios according to the parameters of the wire electrical discharge machining and their diverse levels.

Step 5: Obtain both the delta values and the optimal parametric settings for the parameters.

Step 6: May the values under the response table to the FAHP platform.

Step 7: Institute the FAHP procedure through linguistic term definition and analysis.

Step 8: Defuzzify the parameters to interprete the results

The criteria adopted in the TAHP method

A key method of the proposed integrated method is the Taguchi method. However, while implementing, this method, particularly at the point of introducing the signal-to-noise ratio to the orthogonal array, a decision criterion is launched where the parameter is analyzed in terms of what benefits it brings to the system. This could be from three perspectives, notably (1) where a parameter needs to be increased in value but its increase is beneficial to the system. In this case, it is called the larger-is-better; (2) a situation where a parameter should be reduced in value but this reduction favours the attainment of the system goal. Hence, the smaller-is-better criterion is adopted; and (3) a case where whether one increases the value of a parameter or reduces it, there is no effect. This case is referred to as the nominal-the-best situation.

3.2 Fuzzy-analytical hierarchical process (fuzzy-AHP)

Approaching the work using a fuzzy analytical hierarchical process and using the average of the value gathered on the field using a questionnaire, based on the same parameters considered in the work above, we can come up with some analysis and the procedure followed later is explained here. Fuzzy AHP is all about converting linguistic terms into membership functions. In this case, we will be considering the triangular shape method. This triangular shape depicts the membership function, and under it, we would be choosing the geometric mean value (fuzzy AHP). The fuzzy value is represented using Equation (1)

$$\mu\bar{A} = \bar{A} = (1, 2, 3) \text{ fuzzy numbers} \quad (1)$$

Fuzzy scales:

0	No Importance
1	Equal importance
2	Moderate importance
3	Strong importance
4	Very strong importance
	Intermediate values include (0.5) (1.5) (2.5)

The next thing to do is to generate a table of figures for based on the questionnaires administered to professionals in the field. These values were generated based on the ranking of each parameter over the other. An example of the questions answered is the importance of one parameter over the other when it comes to optimizing a WEDM process. The next step would be to generate the fuzzified pairwise comparison matrix. While doing for the reciprocal value which is on the other side of the table, the value of the higher reciprocal value is kept at the left, while the value for the higher reciprocal value is kept on the right. This is to maintain balance. We would calculate the fuzzy geometric mean value and get this as the product of the corresponding values to the power of ¼

$$(l_1 \times m_1 \times u_1)^{\frac{1}{4}}, (l_2 \times m_2 \times u_2)^{\frac{1}{4}},$$
$$(l_3 \times m_3 \times u_3)^{\frac{1}{4}}, ...(l_6 \times m_6 \times u_6)^{\frac{1}{4}}$$
$$= (l_1 \times l_2 \times l_3 \times l_4 \times l_5 \times l_6, m_1 \times m_2 \times m_3 \times$$
$$m_4 \times m_5 \times m_6, u_1 \times u_2 \times u_3 \times u_4 \times u_5 \times u_6)^{\frac{1}{4}}$$

The next step would be to calculate the weight for all values using the formula for fuzzy weight which has been written above and whose values can be seen in the table and raising them to the power of ¼

($\bar{r}_i$ is the product of corresponding values of *l*, *m*, *u* raised to the power of 1/4)

The next step would be to calculate the weight for all values using the formula for fuzzy weight

Fuzzy weight $\overline{\omega}_i = \bar{r}_i \otimes (\bar{r}_1 \otimes \bar{r}_2 ... \otimes \bar{r}_n)^{-1}$ (2)

This is achieved by adding all the geometric mean values

$$\bar{A}_1 \otimes \bar{A}_2 = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2)$$
$$= l_1 \oplus l_2, m_1 \oplus m_2, u_1 \oplus u_2 \quad (3)$$
$$\bar{A}_1 \oplus \bar{A}_2 \oplus \bar{A}_3$$
$$= l_1 \oplus l_2 \oplus l_3, m_1 \oplus m_2 \oplus m_3, u_1 \oplus u_2 \oplus u_3 \quad (4)$$

Taguchi method

Introducing the signal-to-noise ratio equation and considering the smaller the better, we have

$$SNR = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right) \quad (5)$$

Introducing the signal-to-noise ratio equation and considering the larger the better, we have

$$SNR = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{Y_i^2}\right) \quad (6)$$

Where *n* is the number of parameters considered in the operation,

Y_i is the parametric definition

4. Results and discussion

In this section, the Taguchi analysis was first performed and the integrated results were coupled with the fuzzy analysis. However, for conciseness, researchers referred to Ikedue and Oke [18], which contains the results of the Taguchi analysis that the present authors adopted. The stages covered are the transformation of the factor-level table into the orthogonal array and the development of the signal-to-noise ratios into the response table. Thus, only the response table is extracted from Ikedue and Oke [18] and presented at a later stage where the results of the fuzzy analytic hierarchy are available for integration with the Taguchi results. Consequently, the starting point in this analysis is the display of the pairwise comparison table, obtained when the factor-level table in Muniappan et al. [28] was transformed. Since these results are the experts' judgments from fifteen respondents whose filled questionnaires were analyzed and grouped for interpretation, the information developed is the basis of the analysis.

4.1 Motivation for eliciting expert opinion

Traditionally, it is required to solicit experts' opinions while computing the performance of the wire electrical discharge machining (EDM) process using the AZ91 magnesium alloy. However, the alternative would have been to use the collected data within the plant. Unfortunately, no record keeping exists as the experiments whose data has been analyzed, i.e. Muniappan et al. [28] are restricted to the laboratory and no long-term study of the process to permit documentation of important data was made. Hence the limited data quantity for the wire electrical discharge machining process for the AZ91 magnesium alloy presents difficulty to model the optimisation cum fuzzification problem accurately. Consequently, expert opinion from the field, among those who are exposed to the EDM process is required. Furthermore, the quantitative data inputs from the experts will reveal the current level of development of the EDM practices and the capabilities of various systems available within the Nigerian system whose questionnaire administration territory is domicile. From the survey, respondents were able to discuss their views on the future development anticipated from the EDM system. They also mentioned how they had experience in dealing with the wire EDM process. These insights help improve the current practices of the wire EDM process and open the way for more development in Nigeria and other developing countries that share their growths with Nigeria. Besides, the expert opinion may be helpful as the main component of the fuzzy analytic hierarchy process. Then the Taguchi methods could be augmented with the fuzzy outcomes of the fuzzy analytic hierarchy process in modeling the combined Taguchi-FAHP method.

Furthermore, this study discusses the integration of the Taguchi and the fuzzy analytic hierarchy (FAHP) process methods. It is noted that the proper execution of the FAHP aspect of the wire EDM process pursued in this work is essential for adequate planning of the wire EDM process and the proper prediction of the optimal parametric settings of the process parameters in an uncertain and imprecise environment. Though a previous study on the Taguchi-analytic hierarchy process methodical application in the processing of the AZ91 magnesium alloy has deployed laboratory experimental data on the wire EDM process, however, it is known that the conditions under which the experiments were performed may introduce errors in the data and hence the wire EDM decision making and this makes these data inadequate for decision making. While pursuing the alternative route, the expert opinion has been found as a viable approach to providing reliable decision-making. In the present context, an expert is a technically skilful person who has acquired broad training and is knowledgeable in the wire electrical discharge machining area. Thus, this expert provides a formal judgment on the issue of preference for one electrical discharge machining parameter over the other. The use of expert opinion in providing reliable judgments has been observed in various fields where the fuzzy analytic hierarchy process has been used and in several other studies outside the fuzzy application environments in aerospace, nuclear and chemical industries [32].

Besides, it was observed that studies' regarding the application of expert opinion within the framework of wire electrical discharge machining area seem to be almost completely omitted in its fusion to an analytic hierarchy process or fuzzy analytic hierarchy process except for the study by Ikedue and Oke [18]. Consequently, this article targets filling in the gap and then provides a practical avenue of introducing expert opinion as part of a modelling process where it is embedded in the fuzzy analytic hierarchy process that is integrated with the Taguchi method as the Taguchi-fuzzy analytic hierarchy process.

4.2 Analysis of expert opinion

It is worth noting that the researchers can decide to use each respondent's work to conduct an analysis. However, instead of doing this, the researchers sorted out the work. However, in gathering of the data used for the work, the researchers picked similar inputs from various respondents. In some all the fifteen respondent's work was used, However, at a point in time, some specific inputs from certain respondents would multiply the whole work since a value of zero had been entered as an input. But at any point where a respondent's result for that particular aspect is skipped, then being aware that in fuzzy a reference point is needed, i.e. a pivotal point where there are other intermediate values around them, the next step is to proceed to a table. The table used has its first row (pulse on time) containing these numbers 1, 2, 3, 1, 2 and 3. On the second row (pulse off time), there is 0.5,1,2,3. Notice that these values are before finding a pivotal point. These are the total for all the respondents. For the pulse content, there is 1, 0.33, 0.5, 1, 2 and 3. For gap voltage, there is 1, 0.33, 0.5, 1, 2 and 3. For wire feed, there is 0.5, 1, 0.33, 0.5, 1 and 2. For the wire tension, there are 0.33, 0.5, 1, 0.33, 0.5, 1 and 2. Now finding the pivot around them with intermediate values the researchers were able to come up with the first row (pulse ion time) as 1, 1, 1. The second row (pulse off time) has 1, 2, 3, and the third row (pulse current) has 2,3,4 while 1,1,1; 1,2,3 and 2,3,4 for each of gap voltage, wire feed and wire tension, respectively, were recorded. Now as an adjustment to the analysis, 4 is introduced as very strong because if the pivot around 3 is to be found, there is a need for a value greater than that of 3 service 3 is an input, the other values around it are 2 and 4. At this point, there is an interesting aspect that would be further studied. This is to consider some decimals as the pivotal points around the focal points that are being used. Consider the fuzzified pairwise comparison table, Table 1.

Table 1 Lower, middle and upper values for the fuzzified comparison matrix

	Parameters					
	A	B	C	D	E	F
A	(1, 1, 1)	(1, 2, 3)	(2, 3, 4)	(1, 1, 1)	(1, 2, 3)	(2, 3, 4)
B	(0.33, 0.5, 1)	(1, 1, 1)	(1, 2, 3)	(2, 3, 4)	(1, 1, 1)	(1, 2, 3)
C	(0.25, 0.33, 0.5)	(0.33, 0.5, 1)	(1, 1, 1)	(1, 2, 3)	(2, 3, 4)	(1, 1, 1)
D	(1, 1, 1)	(0.25, 0.33, 0.5)	(0.33, 0.5, 1)	(1, 1, 1)	(1, 2, 3)	(2, 3, 4)
E	(0.33, 0.5, 1)	(1, 1, 1)	(0.25, 0.33, 0.5)	(0.33, 0.5, 1)	(1, 1, 1)	(1, 2, 3)
F	(0.25, 0.33, 0.5)	(0.33, 0.5, 1)	(1, 1, 1)	(0.25, 0.33, 0.5)	(0.33, 0.5, 1)	(1, 1, 1)

The question is looking at the interaction of the A and A, the (1,1,1), how will it interact? The (1,1,1) appears on the diagonal of the table and stands for equal importance. It is the importance of a particular parameter over itself. It cannot be said that a parameter is more important than itself or less important than itself. However, a parameter is equally important to itself. In the questionnaire, the researcher may ask "What is the importance of a parameter to itself?" For instance, what is the importance of pulse on time over pulse on time, it is 1. However, to express it as a fuzzy number, there are elements of 1, each representing the lower, middle and upper terms shown. This (1, 1, 1) is the rule for the formation of the table concerning the diagonals.

Consider the first row and the second column, which shows the interaction between A and B where there is (1, 2, 3), it is essential to explain how to obtain these values as opposed to how it is done in the analytic hierarchy process. For a deep understanding of the problem, the analysis of the questionnaire is made to explain how it is obtained practically from what the experts have filled. There are already given inputs (values) from the questionnaires for each of those inputs, the other members before and after the idle members are the associated values for the particular members that are in the middle. Notice that three members are required for a fuzzy AHP to work with.

From the questionnaires, the researcher captured those respondents that have entered, 2 as their inputs from the fifteen respondents for pulse off time over pulse on time. All the inputs will be used and the average obtained. The average will still be 2. There will not be any averages that will be decimals because the researchers have not selected a mixed figure such as 2 and 3. Although some respondents entered 3 while others entered 2, all those that have entered 2 have been strictly selected. Keeping those who have entered 3 aside, it is possible to develop another table for all the respondents who have entered 3 for that requirement. If this idea is pursued, fifteen different versions of the table will remerge. However, for simplicity, the approach is taken because if the other approach is used, the researchers stand the risk of getting decimals that will be chilling to fix the lower and upper terms, which will be uniform throughout the analysis and still permit the use of fuzzy AHP. Thus, to resolve this issue, the averages of all the results are obtained but it will be extremely difficult to peg the intermediate values for the fuzzy analysis. To illustrate this difficulty, say there are fifteen different inputs for a particular parameter, and the average for all the inputs is 1.93. How do we find the other intermediate average? It is easier when one is dealing with a whole number like 1. It may be easier if one is considering numbers like 1.5 or 1. Otherwise, obtaining the intermediate values will be challenging. This may only be possible if the researchers define what the intermediate values will be and if it will not be uniform for the whole work, it means that a standard intermediate value is not possible. Considering this situation while defining the fuzzy scale the researcher is also defining the intermediate values.

Table 2 Product of lower, mid and upper values

Parameters	l_n	m_n	u_n
A	4.00	36.00	144.00
B	0.67	6.00	36.00
C	0.17	1.00	6.00
D	0.17	1.00	6.00
E	0.03	0.17	1.50
F	0.01	0.03	0.25

In Table 2, the first column is represented by factors with the last column showing the last three terms as the lower, middle and upper entries, often called fuzzy members. The row contains factors A, B, C, D, E and F. On the first row, the values seen are 4, 36 and 144. These values are the products of the lower, middle and upper elements of lower, middle and upper elements of Table 1. Considering how the value 4 was computed, the researcher needs to check the first row of Table 1. Here, the first component 4, in Table 2 is the multiplication of all the lower values obtainable in the second row of Table 1. The individual values to yield it are the products of 1 (under the cell AA), which is the first component of the fuzzy number), 1 (under the cell AB, which is the first component of the fuzzy number), 2 (under the cell AC, which is the first component of the fuzzy number), 1(under cell AD, which is the first components of the fuzzy number), the value 1 (under cell AE, which is the first component of the fuzzy number), and the value 2 (under cell AF, which is the first component of the fuzzy number). Similarly, by picking all the middle values in the cells AA, AB, AC, AD, AE, and AF, which are 1, 2, 3, 1, 2, and 3, their product is 36. Furthermore, the value of 144 under the term u_n of the first row of Table 2 is obtained from the product of upper values in Table 1 of 1, 3, 4, 1, 3, 4 to yield 144. The same procedure is then used to compute all other entries in Table 2 for the remaining rows and columns.

Table 3 shows the values for the fuzzy geometric mean values and they are represented by the r bar with subscript *i*. There are still *l*, *m* and *u* at the columns and A to F on the row aspect.

Thus, for the researcher to be able to gather the information on this aspect, the researcher needs to raise all the values obtained in Table 2 to a power of 0.17, which is the same as 1/6. To obtain each of the values under Table 3, the following statements are true. Under the first column of the first row, the value corresponding to this in Table 2, which is 4, is raised to the power of 0.17 to yield 1.26. Notice the power to which each value is raised is 1/6 being the reciprocal of 6, where 6 is the number of parameters considered. The same is done for the values in the second and third columns of the first row for Table 2, i.e. 36 and 144, where the $36^{0.17}$ and $144^{0.17}$ yields 1.82 and 2.29, respectively. Consequently, all the other values in Table 2 are computed likewise. However, there is a total value on the last row of Table 3, which is the addition of the numbers in each column. For the column *l*, the researchers added 1.26, 0.94, 0.74, 0.74, 0.56 and 0.46 to yield 4.70. The same is done for the middle and the upper values i.e. *m* and *u*, respectively.

To achieve the next step, we will consider the fuzzy geometric mean value, which had been earlier calculated. The reciprocals of the fuzzy geometric mean values were also calculated. Consider the total for the fuzzy geometric mean values, the reciprocals of those values are to be obtained. In using it to multiply the fuzzy geometric mean values, the researchers alternated the values of the lower and upper fuzzy numbers while keeping the middle values constant. Thus, to obtain the values in Table 4, the values in each column and row are worked on to obtain their reciprocals. In this case, the reciprocals of each of the total values in Table 3 are first obtained as 1/8.67, 1/6.47 and 1/4.70, respectively for columns 1, 2 and 3. Thus, in using these reciprocal values to multiply the values of the geometric mean brought from Table 3, the values of the lower and upper terms are to be alternated while keeping the middle values constant. Thus, consider the values 4.70, 6.47 and 8.67 as the lower, middle and upper values as contained in the total cells of Table 3. After finding their reciprocals, which are 1/4.70, 1/6.47 and 1/8.67, respectively, the researchers will alternate the lower values and the upper values of 1/4.70 and 1/8.67, respectively. This will then be used to multiply the fuzzy geometric values while the reciprocals of the total for the middle term remain unchanged. To be specific, to alternate the lower and upper values, where there is 1/4.70, it will be moved to the right under the column containing the upper values and where there is 1/8.67, it will be moved to the left under the column containing the lower values. Here the values for 1/6.47 in the middle remain unchanged. In essence, 1/8.67 and 1/4.70 now become the lower and upper values, respectively. These values are then used to multiply the fuzzy geometric mean values.

Table 3 Fuzzy geometric mean value and its reciprocal

	Fuzzy geometric mean value ($\bar{r}_i$)			Reciprocal of fuzzy geometric mean value (A^{-1})		
Parameter	*l*	*m*	*u*	*L*	*M*	*U*
A	1.26	1.82	2.29	$\frac{1}{8.67}$	$\frac{1}{6.47}$	$\frac{1}{4.70}$
B	0.94	1.35	1.82	$\frac{1}{8.67}$	$\frac{1}{6.47}$	$\frac{1}{4.70}$
C	0.74	1.00	1.35	$\frac{1}{8.67}$	$\frac{1}{6.47}$	$\frac{1}{4.70}$
D	0.74	1.00	1.35	$\frac{1}{8.67}$	$\frac{1}{6.47}$	$\frac{1}{4.70}$
E	0.56	0.74	1.07	$\frac{1}{8.67}$	$\frac{1}{6.47}$	$\frac{1}{4.70}$
F	0.46	0.56	0.79	$\frac{1}{8.67}$	$\frac{1}{6.47}$	$\frac{1}{4.70}$
Total	4.70	6.47	8.67	$\frac{1}{8.67}$	$\frac{1}{6.47}$	$\frac{1}{4.70}$

The reason for this is explained as follows. When the researcher divided 1 by 8.67, the result is a lesser value than when 1/4.70 is calculated automatically the latter moves to becoming the upper value while the earlier moves to becoming the lower value. These values are then multiplied by the fuzzy geometric mean. Thus, for the first one, one has 1.26 multiplied by 1/8.67. Then the middle value of 1.82 will be multiplied by 1/6.47. For the third one 2.29 is multiplied by 1/4.70 (Table 4), expressed as $\overline{\omega}_i$. The corresponding results are on the right-hand side of Table 4. These values are 0.15, 0.28 and 0.49, respectively. The same procedure is implemented for the remaining values on the columns and the rows. With the computations done so far, what remains is the next aspect, which is to find weights. Notice that what was earlier obtained are the fuzzy weights. So, the new computation will be finding the average of the upper, lower and middle values. But the new term is called the centre of area. For the first one, we will have (0.15 + 0.28 + 0.49) divided by 3 to yield 0.30. So, the same procedure is repeated for others and their corresponding answers are 0.23, 0.18, 0.18, 0.14 and 0.10 for parameters B to F, respectively. Now, the researchers need to obtain the total of the column, which is obtained as 1.13. Further calculations involve the computation of weights of factors against the normalized weight, we are aiming at making the total weight to be unity i.e. 1. To achieve this, the researchers divided each of the values for each unit by the total. For the first item, the researchers obtained 0.30 divided by 1.13, which gives 0.27. The same calculation is done to others to complete the computations (Table 4). The next aspect is to obtain information on normalized weights. This normalized weight is brought against the signal-to-noise ratios, in Table 5.

Table 5 is a placement of the normalized weights against the signal-to-noise ratios. Table 6 is the response table introduced from the Taguchi work in Ikedue and Oke [18]. For Table 5, in the first column, there are two entries, where the values in the brackets are the weights while the values outside are the normalized weights. The second column has the signal-to-noise ratios from the Taguchi calculations. The next step is to multiply the response table against the normalized weights. It means that on the first row, the researchers see the fuzzy AHP unified weights (Table 6). Under the weights, the researcher could observe the symbols A to F for the parameters being considered (Table 6). Under these are the values in different levels, from level 1 to level 3. Next is to multiply each of the unifying weights of each parameter against each level. For instance, 0.27 is multiplied by -37.80 to obtain -10.21, which is the value placed in Table 8 at the intersection of level 1 and parametric symbol A. Afterwards, the value of the delta and rankings are obtained. To obtain the delta values for the levels, the maximum value for each parameter minus the minimum value for each parameter is obtained. The delta values obtained are 0.08 to the last value of 0.01

along the row containing delta values for the factors. What the researchers obtained as delta values aided in ranking the parameters from the highest to the lowest value. The highest value is C, which is the pulse current. The second is pulse off time (i.e. B). Notice that the pulse current has a value of 0.81 while the pulse off time has a value of 0.09. The third parameter is A (pulse on time), which has a delta value of 0.08. The fourth position of the parameter with a value of 0.05 is for the gap voltage. The fifth position is wire tension (F) has a value of 0.01. The sixth position is for the parameter E (wire feed) which has a value of 0.00. The optimal parametric settings for the work done is $A_1B_1C_1D_1E_1F_1$ which is interpreted as 106 units for pulse on time, 40units for pulse off time, 70 units for pulse current, 20 units for gap voltage, 4 units for wire feed 4 units for wire tension (see Table 7).

Table 4 Fuzzy weight computation

Fuzzy weights ($\overline{\omega}_i$) = ($\overline{r}_i$) $\otimes$ $\overline{A}^{-1}$	Fuzzy weights ($\overline{\omega}_i$)	Weight (ω) = Center of area, COA = $\frac{l+m+u}{3}$	Normalized weight
(1.26, 1.82, 2.29) $\otimes$ $\frac{1}{8.67},\frac{1}{6.47},\frac{1}{4.70}$	(0.15, 0.28, 0.49)	0.30	(0.30/1.13) = 0.27
(0.94, 1.35, 1.82) $\otimes$ $\frac{1}{8.67},\frac{1}{6.47},\frac{1}{4.70}$	(0.11, 0.21, 0.39)	0.23	(0.23/1.13) = 0.21
(0.74, 1.00, 1.35) $\otimes$ $\frac{1}{8.67},\frac{1}{6.47},\frac{1}{4.70}$	(0.09, 0.15, 0.29)	0.18	(0.18/1.13) = 0.16
(0.74, 1.00, 1.35) $\otimes$ $\frac{1}{8.67},\frac{1}{6.47},\frac{1}{4.70}$	(0.09, 0.15, 0.29)	0.18	(0.18/1.13) = 0.16
(0.56, 0.74, 1.07) $\otimes$ $\frac{1}{8.67},\frac{1}{6.47},\frac{1}{4.70}$	(0.06, 0.11, 0.23)	0.14	(0.14/1.13) = 0.12
(0.46, 0.56, 0.79) $\otimes$ $\frac{1}{8.67},\frac{1}{6.47},\frac{1}{4.70}$	(0.05, 0.09, 0.17)	0.10	(0.10/1.13) = 0.09
	Total	1.13	1.00

Table 5 Normalised weight versus signal-to-noise ratios

Normalized weight, *NW*	$-10\log(1/n)\sum Y_i^2$
(0.30) = 0.27	-34.81
(0.23) = 0.21	-34.83
(0.18) = 0.16	-34.85
(0.18) = 0.16	-37.92
(0.14) = 0.12	-37.93
(0.10) = 0.09	-37.94
-	-40.63
-	-40.63
-	-40.64
-	-38.16
-	-38.17
-	-38.16
-	-40.63
-	-40.63
-	-40.63
-	-35.82
-	-35.84
-	-35.82
-	-40.76
-	-40.75
-	-40.76
-	-36.20
-	-36.19
-	-36.20
-	-38.51
-	-38.50
-	-38.50

Table 6 Taguchi-fuzzy AHP unified weighted response table

Fuzzy AHP unified weight →	0.27	0.21	0.16	0.16	0.12	0.09
Level ↓	Parametric symbol A	Parametric symbol B	Parametric symbol C	Parametric symbol D	Parametric symbol E	Parametric symbol F
Level 1	-37.80* (-10.21)	-37.91* (-7.96)	-35.62* (-5.70)	-37.99* (-6.08)	-38.16* (-4.58)	-38.16* (-3.43)
Level 2	-38.21 (-10.32)	-38.25 (-8.03)	-38.20 (-6.11)	-38.17 (-6.11)	-38.16 (-4.58)	-38.16 (-3.43)
Level 3	-38.48 (-10.39)	-38.32 (-8.05)	-40.67 (-6.51)	-38.33 (-6.13)	-38.17 (-4.58)	-38.17 (-3.44)
Delta	0.08	0.09	0.81	0.05	0.00	0.01
Rank	3rd	2nd	1st	4th	6th	5th

*Values in brackets are those after the multiplication of the average SN ratios with the fuzzy AHP unified weights

Table 7 Process Parameters and their levels [18],[28]

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

4.3 Comparison of TAHP and TFAHP methods

It is essential to discuss a comparison of the results obtained between the TFAHP and TAHP methods to ascertain the differences and similarities between them. Here, the data on the optimal parametric setting, delta values and the ranks obtained by the two methods are compared. This section compares the work done earlier on the optimisation of the wire electrical discharge machining process using the Taguchi-based analysis-analytical hierarchy process (AHP), against the optimisation of wire electrical discharge machining process parameters on A791 magnesium alloy using the Taguchi-based-fuzzy analytical hierarchy process with the geometric mean option. By comparing the studies, at the results level, the following could be discussed. It was noticed that the ranking did not change but the results changed. For the TAHP method [18], the ranking occurred in a different order but the first and the last positions were assigned to pulse current and wire feed, respectively. For the delta values, we had 0.97 for the pulse current while considering Taguchi AHP [18] against 0.81 when using the Taguchi-fuzzy analytical hierarchy process (current study), which is a reduction of 16.49%. The delta value could be conceived as the proportion of the weight changes at the level value of a parameter when all the possible levels are considered. In this case, three levels are considered, namely levels 1, 2 and 3.

Furthermore, the decrease in the delta values between TAHP to TFAHP reveals the degree of uncertainty captured by the method. Previously, wrong interpretation of results was possible and error in decision making was also possible. For the pulse off time parameter, the delta value for the TAHP method is 0.07 [18] against the delta value of 0.09 (current study) for the TFAHP method. Here, we experienced an increase and the difference in percentage value is 28.57%. Next, the pulse on time is considered. Here, the delta value for the TAHP method is 0.18 [18] while for the TFAHP method, the delta value is 0.08 (current study). Here, we experienced a decrease in the delta value and the difference in value is 55.56%. For the gap voltage parameter, the delta value for the TAHP is 0.05 [18] against the delta value for the TFAHP method, which is 0.05 (current study). Here, the value is the same. For the wire feed parameter, the delta value for the TAHP is 0.00 [18] against the second one, TFAHP, where we have a delta value of 0.00 (current study). Here the value is also the same. For the wire tension parameter, the delta value for the TAHP is 0.00 [18] against a value of 0.01 for the TFAHP (current study), which is an increase. From the researchers' knowledge, it was observed from the evaluation that there were both increase and decrease in the performance level when the TFAHP was tested against the TAHP method.

These evaluations are based on the parameters of the wire electrical discharge machining and using the delta values, which measure the changes of a parameter across the various levels that the practical data was collected. For the pulse on time, we experienced a decrease. For pulse off time, we experienced an increase. For pulse current and wire feed, there were decreases, gap voltage showed the same value while wire tension showed an increase in the delta values from the application of TAHP to TFAHP. Overall, it is noted that we have more decrease events than increase events. Consequently, the application of the TFAHP method caused a general decrease in the delta values. As for the ranking of the parameters, except for the best and worst parameters of pulse current and wire feed, respectively, which were the same, other results in ranks show variations and disagreements comparing the ranks using the TAHP method and TFAHP method. However, these differences are not easily quantified.

5. Conclusions

The work considered is an analysis that integrates each of the three methods of Taguchi with the fuzzy analytic hierarchy process to process the AZ91 magnesium alloy in the wire electrical discharge machining process. In a related previous article, the analytic hierarchy method was used on the Taguchi method. However, it is realized that human-controlled systems have difficulties at times with the inputs. In this case, the operator may unconsciously record imprecise values of inputs, and the machine may show correct values of inputs due to some unnoticed faults and uncertainties that could arise in computation. Unfortunately, in this instance, the analytic hierarchy process is not capable of providing useful results in this case where imprecise inputs are given. Thus, as it is understood that the fuzzy analytic hierarchy process could accommodate input categories involving data vagueness, and imprecise and distorted data, it is applied and added to the Taguchi optimization framework as the Taguchi-based fuzzy analytic hierarchy process (geometric mean method). The experiment entails combining the Taguchi-based analysis and fuzzy analytic hierarchy process to best optimize the wire electrical discharge machining process; the best suitable parameters are explored in a robust system that may fail to produce precise inputs. First, for the Taguchi-based analysis, data is considered from Muniappan et al. [28] and majorly focused on the parameters used by the authors' analysis. These parameters include pulse on time, pulse off time, pulse current, gap voltage, wire feed and wire tension. The parameters were considered at three levels.

This article was analyzed using the Taguchi method first according to the procedure indicated in Ikedue and Oke [18]. The second part of the analysis was conducted using data gathered from the questionnaires submitted to various experts in the field. It is worth noting that it is the same set of data collected for the analytic hierarchy process discussed in Ikedue and Oke [18] but only differs in the analysis of the data as the present study adopted a fuzzy perspective to the problem. The questionnaires targeted engineers, and process personnel (technically skilled). The data for use in the fuzzy analytic hierarchy process were gathered through the questionnaire administration. The main conclusions of the work are as follows.

1. The authors were able to obtain optimum parametric settings from a fuzzy perspective, for combined Taguchi analysis and fuzzy analytic hierarchy process. The optimal parametric setting is $A_1B_1C_1D_1E_1F_1$ interpreted as a pulse on time (160units), pulse off time (40 units), pulse current (70 units), gap voltage (20 units), wire feed (4 units) and wire tension (4 units).
2. For the delta values, considering Taguchi AHP against when using the Taguchi-fuzzy analytical hierarchy process, we had a reduction of 16.49% for the pulse current, an increase of 28.57%, for the pulse off time, a decrease of 55.56%, for the gap voltage, no changes, for wire feed, no changes, for wire tension, an increase of roughly 10%.
3. The ranking of the two methods was compared involving the proposed method in this article and the previously obtained rank in Ikedue and Oke [18] where a combination of the Taguchi method and analytic hierarchy process was made. The ranking of the T-AHP and T-FAHP did not change for the best and the worst parameters, which are pulse current and wire feed, respectively.

Moreover, the strength of this article has been discussed in the introductory section along with the strength of the Taguchi method, the analytic hierarchy process method and the method of fuzzy system. However, there are some limitations of the proposed method to consider. The analysis of the wire electrical discharge machining method parameters, although represented by the proposed method, may be viewed as partially effective in the absence of associations (interactions) among the parameters. Therefore, instituting a method like DEMATEL (Decision MAking Trial and ELimination) to stimulate the interactions of the parameters will be a worthwhile future endeavor. In the combination method proposed, the fuzzy method is an important component. However, for fuzzy systems, the task of setting exact rules coupled with the membership functions is a challenging issue. Thus, the model may be influenced by the weakness of the fuzzy system. Notwithstanding, overcoming this barrier may be aided by the use of questionnaires targeted at the experienced decision makers within the wire electrical discharge machining industry. Moreover, although past studies have neglected the effects of particular parametric behaviour on the overall outcome of the system, sensitivity analysis of parameters is therefore recommended as a future study. Furthermore, in this article, the authors have only applied the triangular membership functions to evaluate the fuzzy values, which had been expressed using some symbols. As a future research direction, the fuzzy representation may divert to other aspects such as cuboid polynomial curves, Gaussian distribution function, quadratic polynomial curves, piecewise linear functions and sigmoid curves to solve the issues associated with membership representation functions to assess the fuzzy values. Thus, in the future, the proposed method could also compare these functions on their applications to the processing of AZ91 magnesium alloy in wire electrical discharge machining. These new analyses may also be compared with the results from the triangular membership functions proposed in the present work.

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