Kufa Journal of Engineering
Vol. 15, No. 4, October 2024, P.P. 157-185
Article history: Received 23 April 2024, last revised 3 July 2024, accepted 14 August 2024

ANALYSIS OF THE THERMAL FRICTION DRILLING PROCESS FOR EFFECTIVE PARAMETRIC CHOICE ON THE DRILLING OF AISI 304 STAINLESS STEEL USING THE FUZZY AHP-MOORA METHOD

Ugochukwu Sixtus Nwankiti[1], Adeyinka Oluwo[2], Manasseh Olusegun Oyekeye[3], John Rajan[4], Swaminathan Jose[5], Rajeshwar Kadadevarmath[6], Sunday Ayoola Oke[7], Samuel Bolaji Aderibigbe[8], Samson Oluwaseun Odudare[9]

[1,2,3,7,8,9]Department of Mechanical Engineering, University of Lagos, Lagos, Nigeria

[4] Department of Manufacturing Engineering, Vellore Institute of Technology, Chennai, India

[5] School of Mechanical Engineering, Vellore Institute of Technology, Chennai, India

[6] Amruta Institute of Engineering & Management Sciences, Bidadi, Bengaluru, India

*** Corresponding author: sa_oke@yahoo.com.**

https://doi.org/10.30572/2018/KJE/150411

ABSTRACT

Attaining effective quality control of drilled samples in thermal friction drilling is a challenge considering the disproportionate allocation of drilling resources to parameters. Therefore, it is essential to select the appropriate parameters and allocate their scarce resources based on requirements. This paper chooses the effective and the best parameters of the drilling process during the processing of AISI 304 stainless steel using the fuzzy-AHP-MOORA method. The analytic hierarchy process is deployed by stating the criteria and alternatives. A pairwise comparison is made with the outcome introduced into a fuzzy framework which interpretes the obtained values from an input to an output vector via a rule (linguistic the terms) set. The result is expressed as responses to options compared to the objectives as ratios. The input parameters are the feed rate, friction angle, rotational speed, friction contact area proportion, tool cylindrical region diameter and workpiece thickness. In turn, the responses are the roundness error, radial force, dimensional error, axial force, bushing length and hole diameter. It was found that experimental trials 12, 14 and 8 with the respective differences between beneficial and non-beneficial values of 0.2133, 0.2076 and 0.1083 obtained the respective positions of 1st, 2nd and 3rd. The discretized fuzzy weights place the bushing length as the best while the second position is shared equally by all the other responses. The model was successful in reducing the imprecision in the parameters and the greatly improved response was the bushing length.

KEYWORDS

Friction, drilling, axial force, feed rate, rotational speed, workpiece, bushing length.

1. INTRODUCTION

Contemporary industrial production of goods exists in the automobile industry, industries for the production of circuit boards and heat sinks as well as those dealing with heating, ventilation and air conditioning systems, among others. In all these industries, production technologies and the durability of machine tools are important. Extensive studies have been documented in this regard. For example, (Baksa et al. ,2015) compared the durability of various milling tools using the DINX210Cr12 as the workpiece material. (Belov et al. ,2024) compared the durability of carbide cutting tools using the (Ti, Al) N-Cu and (Ti, Al)N-Ni coatings on the workpiece surfaces to process steels, 09G2S and ER302-Sh, respectively. (Manokhin et al. ,2020) responded to the durability challenge in tools by analyzing the influence of protective PVD coatings of diverse compositions. (Volkhonskii et al. ,2015) ensured the durability of an edge tool by a hardening process involving a coating-carbide cutting insert system of monolayered coatings and multilayered coatings. The importance of adopting these technologies and managing the durability challenge is that they improve the quality of the materials transformed throughout the various stages of the manufacturing process. They improve plant efficiency through enhanced productivity and reduced material wastage.

From the above discussion, it is understood that production technology is a centre point for industrial progress and friction drilling is a key focus of the present discussion. Friction drilling is a comparatively new non-traditional hole-making process, which is noted for its success in producing chipless drilling tasks in hole-making, for various metal composites (Albarbary et al., 2022; Chityal et al., 2022). The process has emerged with immense success in displacing the conventional drilling process, which drills by cutting the workpiece. The deviation is that instead of the earlier mentioned workpiece cutting approach, the friction drilling method forms bushes through elevated heat generation at the contact region where the rotary conical tool meets the work material (Albarbary et al., 2022; Chityal et al., 2022). During the movement of the tool on the work material, the frictional heat increases the thickness of the sheet metal parts as it makes holes (Albarbary et al., 2022). Nonetheless, (Chityal et al. ,2022) reported that a drawback of the process is that the high heat generation impacts the surface quality of the bush, causing it to have a less shiny and smooth surface. Furthermore, friction drilling has found profound and useful applications in several industries, including aerospace, automotive, oil and gas, electronic packaging, commercial and industrial products and thermal management. (Baraheni et al., 2021; Backar et al., 2020, Bilgin et al., 2017, Somasundaram et al., 2011a,b). In these industries, it is common to find the application of contemporary methods such as ultrasonic vibrations to the thermal aspect of the system.

From the foregoing, friction drilling takes centre stage in industrial production practices and a rough estimate of energy cost for a forthcoming planning period is a difficult task for researchers. Moreover, the choice of appropriate energy requirements during thermal friction drilling, which is a production technology is crucial for economic and energy management issues in contemporary industrial production practices. It is known that gross over/under budgeting of energy requirements may lead to excessive spending in budget implementations since inputs into decision-making will be faulty. Also, in the drilling processing of AISI 304 stainless steel, the concern has been to monitor parameters such as blur formation and responses. However, the failure of the researcher to precisely estimate their thresholds may result in excessive allocation of scarce resources to non-deserving parameters and responses. Consequently, the drilling sector of manufacturing requires novel methods that are straightforward and robust to enhance decision-making in the selection of the best parameters during drilling and also to choose optimal parameters. Therefore, the requirement for new methods of selection is an important research area. This has attained heightened importance among drilling researchers to search for appropriate solutions. Consequently, the analytical hierarchy process (AHP) method is one of the promising selection approaches for drilling processes as it possesses extraordinary advantages, including the following: it is flexible and simple in obtaining selection solutions. The AHP, being flexible, implies that it possesses competence in adapting and learning from drilling data. It is apt to predict or decide on a broad scheme of drilling inputs and responses. Moreover, being simple in finding solutions implies that it offers intelligible and actionable solutions which target the improvement of drilling decisions. In the same perspective, many literature sources have reported that the thermal friction drilling problem with several conflicting input parameters and multiple responses is complicated to solve (El-Bahloul et al., 2015; Nwankiti and Oke, 2022). However, the fuzzy theory has been an effective solution to this complex concern (El-Bahloul et al., 2015).

Besides, the thermal friction drilling process of AISI 304 stainless steel is a complicated real-life problem. To solve this problem, the most suitable alternatives, subject to intangible and tangible criteria must be found. Moreover, the available classical methods of Taguchi-based optimization methods evolved from crisp numerical value computation (Nwankiti and Oke, 2022). This Taguchi orientation is insufficient to solve this problem when confronted with insufficient information on the drilling process due to cost and time limitations. Moreover, since the drilling problem within the scope of optimization has inherent uncertain information within it, combining fuzzy models (i.e. fuzzy sets) with it is necessary for embarking on the right decisions (El-Bahloul et al., 2015). Also, advocates of the fuzzy concept assert that it could be modified easily to enhance the performance of drilling systems. They further promote the use of fuzzy theory as possessing the ability to tackle uncertainty (El-Bahloul et al., 2015). Thus, it is compelling to integrate the fuzzy theory with the AHP as the fuzzy AHP method. However, during the last decade, the MOORA method with outstanding advantages has gained popularity in engineering applications. The MOORA method has been described as simple and flexible. Moreover, given the strong support in the literature for hybrid models, the need to integrate the MOORA method with the fuzzy AHP method to yield the fuzzy AHP-MOORA method is compelling. Thus, this article presents a novel method based on the fuzzy analytic hierarchy process-MOORA (multi-objective optimisation ratio analysis) method (Alinezhad and Khalili, 2019). The proposed method evolves values that promote the best decisions. In this study, the thermal friction drilling process responses and parameters focused on uncertainty reduction and selection for the AISI 304 stainless steel. The criteria influencing the process have been established using the fuzzy analytic process. This provided weights of criteria according to the geometric mean bias. Then, the weights are integrated with the elements of the MOORA method to establish some best and worst parameters from the drilling process. Notwithstanding, the experimental data by (El-Bahloul et al. ,2015) is used to validate the method.

In this paper, research is conducted on the thermal drilling of AISI 304 stainless steel used in the dyeing industries as well as for chemical containers, heat exchangers and welded screens for mining. Particular emphasis is placed on the fuzzification of the crisp members obtained from the transformation of the expert's opinions through a pairwise comparison scheme in the analytic hierarchy process. The purpose is to reduce uncertainty and imprecision. Drilling data is susceptible to uncertainty and imprecision primarily because of systematic error where the limitation of the measurement instrument comes into place. The other reason is random error where the investigators with varying skills in handling the measurements introduce error into the measurement. The research anticipates solving the problem of decision-making in drilling realistically. This study could be helpful for the industry to reveal the heat characteristics during drilling. It offers a structure displaying extensive flexibility for adjusting to concerns arising from a paucity of data on the drilling process. Furthermore, with the idea proposed in this work, technical assistance to overcome drilling quality issues of the AISI 304 stainless steel is provided.

Notwithstanding, comprehensive research on parametric performance improvement in friction drilling revealed that the introduction of optimisation methods such as grey wolf optimizer helped alleviate the convergence performance and aid easy implementation (Nwankiti and Oke, 2022). However, the results still have elements of uncertainty and imprecision caused by the parameters of the friction drilling process. It is also clear that few studies have been detailed using multicriteria tools to analyse the effects of parametric characteristics on the performance of the thermal friction drilling process. Uncertainty and imprecision were also mostly analysed in previous studies but only from the perspective of a combination method of grey relational analysis and fuzzy logic. The recommendation level obtained from the thermal drilling parameters aided in minimizing the thermal drilling parameters with associated advantages to the outputs. However, the study was implemented in an integrated optimization and uncertainty reduction circumstance where the grey relational analysis considered partially available data from experiments. Here, the independence of the fuzzy algorithm from the optimization scheme as well as the grey theory was not adequately considered.

Therefore, the current research aimed to evaluate the effect of introducing the fuzzy AHP-MOORA method on the reduction of uncertainty and to select the most effective parameters while processing the AISI 304 stainless steel through the thermal friction drilling process. The experimental apparatus and design reported by (El-Bahloul et al. ,2015) whose data is used in the present study were drawn from a test rig which comprises two motors. One of the motors performs high rotational speed close to 4500rpm at the maximum and the other motor has a feed rate close to 200mm/min. The tool used in the study was held in position using the standard collets while 18 thermal friction tools were engaged for the experiment.

This article makes an original contribution in the following aspect: It develops a framework for the thermal friction drilling parametric selection using the fuzzy AHP-MOORA method. In the framework starting with using the fuzzy AHP for selection and ascertaining the reduction in uncertainty and imprecision in the evaluation process, the fuzzy scale of comparative importance produces fuzzy numbers. These fuzzy numbers are translated to triangular membership functions which are used to produce pairwise comparison results. Then the fuzzy geometric mean is established to produce weights for the parameters. The fuzzification process of the thermal friction drilling parameters contributes to a deeper understanding of the drilling process. It permits the reduction of uncertainty in the data evaluation process. Overall, integrating this fuzzy AHP method with the MOORA method contributes to the drilling literature on how to solve the multicriteria drilling problem in the face of the paucity of drilling data.

2. LITERATURE REVIEW

With applications in bicycle frames, which house other components as well as usage in heat exchangers that transfer heat between sources and working fluids, friction drilling assists engineers in making holes in metals. Materials are pushed out of the way assisted by frictional heat. However, improvement efforts in friction drilling, are commonly limited to the optimization of drilling resources, analysis of tool characteristics in friction drilling and the reactions of other materials apart from stainless steel, such as brass and aluminium. These research and practice inclinations mentioned above have remained largely the same for several years. Notwithstanding, this article is advocating for a new method of improving the performance in friction drilling. Instead of analyzing friction parameters through the Taguchi-Pareto method and the grey wolf optimization method, the present researchers are proposing the combined fuzzy-analytic hierarchy process-multi-objective optimisation on the basis of ratio analysis. This proposed method has two main strengths: First, using the fuzzy algorithm, a component of the proposed fuzzy–AHP-MOORA method, it is possible to solve the friction drilling problem with an open, imprecise data range and heuristics, which triggers a group of accurate conclusions. Second, the proposed method accounts for beneficial and non-beneficial criteria and concurrently ranks alternatives from a collection of accessible possibilities. In the following sub-sections, the literature is reviewed under the general aspect of friction drilling and the second aspect of the review is multicriteria applications.

2.1. Friction drilling

The following discussions fall under the subheading of friction drilling: The precise fastening of joints in stainless steel using the friction drilling process is critical to regulating the challenges often faced while profiling stainless steel. This includes steel cutting that is central to the use of connectors for steel sheets and tube products. However, some controversies that arise still need to be resolved. At present, it is not clear how to choose the best friction drilling parameters while reducing uncertainty and imprecision during the analysis for decision-making. Moreover, in decision-making, it is found that to generate optimal surface roughness and bush formation during friction drilling, input parameters significantly influence the system. With this are some outputs, which may be obtained according to data availability. Therefore, such outputs having direct effects on the attainment of superior surface integrity and bush length need to be monitored. Accompanied by these outputs is uncertainty in friction drilling. The measurement equipment and the operators are the major parts of this uncertainty and imprecision. This brings a large variability of the friction drilling data, which triggers the corresponding variance in the acceptable limits of errors during friction drilling decision-making. This idea of uncertainty and imprecision in friction drilling deserves a comprehensive investigation to reduce its influence on friction drilling decision-making.

Moreover, recently, government policies across the globe and the response from international and management within organizations in the drilling segment have forced existing drilling organizations to enhance their energy utilization systems. A further attempt by these organizations is to adopt advanced energy-productive and energy-saving systems. Consequently, the idea of thermal friction drilling has attained a heightened significance as an avenue to attain a competitive edge in energy usage despite the highly harsh economic environment globally. Thermal friction drilling is a clean process, which prevents drilling problems like strut-in-objects and drill formation damage since it is a chipless hole-making procedure. Being chipless enables the drilling engineering to reduce the drilling costs while maintaining the quality of the drilled AISI 304 stainless steel. Thus, the chip-less idea is adopted as an efficient way to drill the stainless steel and guarantee no waste at all. Another advantage of thermal friction drilling over conventional drilling methods is its high-reliability process. In this context, the resilience of the system assists the drilling engineer in quickly organising plans to react to maintenance occurrences. In addition, no fasteners are needed in the thermal friction drilling process. Moreover, thermal friction drilling promotes a more cylindrical shape of bored holes than in the greater depth. However, in thermal friction drilling, parametric selection is a principal strategic issue. At variance with most available literature where a single criterion is treated at a time, the assessment and selection of thermal friction drilling optimum parameters for drilling purposes may be identified as an essential multicriteria decision-making problem.

(Stockburger et al. ,2023) used the smoothed particle galerkin approach to simulate the friction drilling of HX220 sheet metal. The experimental results and predictions were in high agreement. (Hamzary et al. ,2023) analysed the influence of variations in the parameters of friction drilling, such as the feed rate, cone angle and tool rotational speed on the surface roughness values as well as the dimensions (which include thickness and height) for the bushing (which is thermally-induced) made of AA6082. The optimization of the drilling parameters was conducted using the response surface methodology. It was concluded that at optimal thresholds, the lowest surface roughness value yields on rotational speed of 1250rpm, a feed rate of 200mm/min and a cone angle of 45°. However, the optimal height was attained when the rotational speed was 1250rpm, the feed rate achieved 200mm/min and the cone angle reached 50°. (Demir and Ozek , 2014) attempted to enhance the bushing shape of AA7075-T651 material using friction drilling. The surface roughness was taken as the output while the feed rate and spindle speed were the key parameters. It was reported that a decrease in the produced heat as a result of the increase in pre-drilled hole diameter was achieved. (Ozler and Dogru ,2013) applied friction drilling to AISI1010 steel material. The responses were taken as petal geometry, washer geometry and bushing height while the input parameters are the drilling speed, cone angle and feed rate. It was reported that the temperature at the hole zone increased while the drilling speeds increased and the feed rates reduced. Also, high drilling speeds enhanced washer geometry and subsequently, an expansion of the bushing height was observed. (Kumar and Hynes , 2019) thermally drilled DP 600 grade-type galvanized steel with rotational speed varied to obtain surface roughness, microstructure, formation of bushing height and microhardness of the thermally drilled holes. The bushing height was found to have improved when rotational speed heightened. Notwithstanding, the petal formation at the outer using the experimental design matrix coupled with the response surface methodology establishes an empirical association of the roundness error with process parameters. The conclusion relates to the influence of input parameters on randomness error. (Bilgin et al., 2015) analysed the friction drilling process by applying the central drill in both numerical and experimental analyses. In particular, the finite element analyses were applied from the analysis made on the deform-3D software based on the finite element method. The torque and axial power as well as the heat transfer coefficient are the focus of the computation on process parameters. It was reported that a decline in the torque and axial force values was noticed while the temperature values of the central drill, and the spindle speed increased. (Urbikain and Perez, 2016) presented a novel approach to processing dissimilar materials for joints using friction drilling and form-tapping procedures. The new method was considered successful and essential for use by a lightweight metal industry that aims to avoid welding beads or conventional bolted joints through nut applications.

(Chityal et al., 2022) conducted experiments to optimize the surface roughness and bushing length using three metaheuristic methods such as genetic algorithm, Jaya algorithm and particle swarm optimization. It was reported that the Jaya algorithm outperforms both particle swarm optimization and genetic algorithm, showing more efficiency and fast solution convergence. (Alabarbary et al., 2022) attempted an approach to enhance the quality of friction-induced bushes in brittle A356 aluminium sheets by conducting a pre-drilling activity to reduce cracks. It was reported that the bushings developed in the pre-drilled sheets avoided crack or petal development when compared with other developed bushes within the solid sheets. Also, there was a reduction in the surface roughness as the rotational speed increased and as well when the feed rate reduced. (Karakoc et al., 2024) analysed the influence of B4C fortification on friction drilling performance considering tribological and mechanical properties of the material. It was reported that the tensile as well as transverse rupture strength was enhanced at 15wt%B4C. Furthermore, a growth of the wear resistance for the friction-drilled Al6063 metal matrix composite was noticed when the B4C content was increased. Nonetheless, the highest thread-stripping strength existed at 10%wt% B4C specimen of the Al6063 composite reinforced with B4C content.

2.2. Multicriteria applications

Under multicriteria applications, several studies have been conducted, including the following: In particular, the literature is reviewed to understand the state-of-the-art in the multicriteria area relevant to the present study is the fuzzy MOORA method. The target papers are those that use fuzzy MOORA independently or in combination or in comparison with other methods in engineering and non-engineering applications. However, important studies on the MOORA method are also reviewed. In searching the literature, the applications of fuzzy MOORA were found in several aspects including the following: Hammering machine design and fabrication (Emovon et al., 2021). Others are agile supply chain processes (Matwale et al., 2016). (Emovon et al., 2021) fabricated a local machine for hammering reviewing, punching and upset forging with an appropriate material selection scheme based on fuzzy multi-objective optimization on the basis of ratio analysis (MOORA). Moreover, (Matawale et al., 2016) deployed a fuzzy MOORA method to compare the performance of activities of a number of the ASC (agile supply chain) in comparison with what is obtained with the fuzzy TOPSIS. (Rane et al., 2021) adopted the multi-objective optimization on the basis of ratio (MOORA), multi-MOORA and Monte Carlo simulation approaches while the Delphi method was used to strengthen the work. The other methods were used to establish the superior fleets for buying decisions. The most advantageous parameters for fleet management and health were separately identified as fuel consumption, CO_2 emission and coolant temperature for fleet management. For fleet health, fuel consumption and revenue generation were chosen as crucial parameters. In the article by (Datta et al., 2013), an efficient system for robust selection decisions was reported based on the most important characteristics of the robots to make the best robot selection decisions using the grey-based MULTI-MOORA approach. (Ranjith et al., 2022) proposed a hybrid method of MOORA-ELECTRE to analyze the machining problem with optimal weights % of the constituent for the AZ91/B_4C_p composite. With the simple-to-comprehend method adopted, the desired optimal weights were selected for the composite. (El-Bahloul et al., 2015) studied the optimal parameters of the friction drilling process while considering the AISI 304 stainless steel. The similarity between this reviewed article and the present is that the current study draws its data from the reviewed article. (Boopathi et al., 2013) analysed the characteristics of three materials, including stainless steel under the friction drilling process. The article is skewed toward the microstructural investigation of the stainless steel material while it deviates from the current study that is interested in reducing uncertainty and imprecision in the process.

Furthermore, with its emergence in 2006, the MOORA method, which was proposed by Brauers and Zavadskas, has experienced substantial applications in diverse areas (Thakkar, 2021). These areas include evaluations of the national economy as in Brauers and Zavadskas (2006) who proposed the use of the MOORA method to the privatisation area in a characteristically transition economy and drew an example to validate the method. Data from a European background was used to validate the methods. Dwivedi and Dwivedi (2018) introduced two methods, namely the MOORA and WSM, to explore the supplier selection concept within the manufacturing domain. Furthermore, using a wide range of cases in side milling, end milling, and face milling and the adoption of the MOORA method, Gadakh (2011) proved the flexibility and potential application capability of the method in the milling arena. Moreso, Fadli and Imtihan (2019) evaluated the performance of honorary teachers using the MOORA approach. Data for the validation of the method was drawn from 18 high schools in the Indonesian territory. The MOORA method aided the identification of superior teachers who merit promotion. Also, Patel and Maniya (2015) choose the optimal value for wire EDM outputs using the MOORA method while drawing experimental data from the EN31 alloy steel with brass wire for the validation of the method. The potentiality and applicability of the MOORA method were proved in the machining scenario.

Although the above articles seem to have discussed selection methods and some biases have been expressed in machining operations (i.e. Gadakh, 2011; El-Bahloul et al., 2015; Patel and Maniya, 2015; Nwankiti and Oke, 2022), selection method incorporating uncertainty reduction in the friction drilling domain is still less reported. In this article, the fuzzy concept is introduced in the situation of the paucity of data and with the obligation of implementing reliable and useful results for decision-making. Unlike the Taguchi-Pareto based method of Nwankiti and Oke (2022), the approach introduces fuzziness in the geometric mean context to improve the uncertainty present in decisions using crips numerical value.

Subsequent to an exhaustive review of the literature, several research gaps in the friction drilling of AISI 304 stainless steel were found. Applications of AISI 304 stainless steel are common in tubing, sinks and pans, among others. The research gaps follow:

- Less attention has been given to the selection and uncertainty analysis on steel material.
- Little studies have been conducted on AISI 304 stainless steel.

- Researchers have focused less on the friction drilling of AISI304 stainless steel.
- In the multicriteria research area on AISI 304 stainless steel, only a few selection methods have been employed.
- Less attention has been paid to the uncertainty and imprecision analysis of the parameters of friction drilling while machining the AISI 304 stianless steel,

3. METHODOLOGY

3.1. Reasons for choosing the fuzzy AHP-MOORA method

The following are important reasons for choosing the fuzzy AHP MOORA method.

- Fuzzy AHP-MOORA method exhibits excellent qualities such as allowing the modeling of uncertainties, enhancing the solutions from parametric considerations and decreasing costs for engineers and process managers.
- Allows criteria to be analysed in hierarchy thus providing a superior focus by the engineer and process owner on the particular criteria and sub-criteria that matter to the friction drilling process.
- Fuzzy AHP-MOORA method has outstanding attributes that exceed most selection methods. Such attributes include more stability and clarity, less computation time, and less numerical calculations compared with TOPSIS and VIKOR, among others. These attributes are the contribution of the MOORA method in the fuzzy AHP MOORA method.

3.2. The friction drilling process and the AISI 304 stainless steel material

In this section, a brief description of the thermal friction drilling process and the AISI 304 stainless steel material are given as follows: In thermal friction drilling, there exists heavy friction while drilling. What happens is that as the AISI 304 stainless steel heats up, it becomes a flow metal. So in drawing holes it will not be achieved mechanically but by pressure and friction combination. In mechanical drilling, threading which usually accompanies drilling is quite difficult to do on the AISI 304 stainless steel. However, the application of friction drilling eliminates the threading process, producing quality drills competitive with what drilling will achieve. Moreover, the AISI 304 is perhaps the most widely used category of steel in practice, referred to as austenitic 18/8 stainless steel given its 18% chromium and 8% nickel content with other stainless steel qualities. In comparison, the AISI 304 stainless steel exhibits less electrical and thermal conductivity properties than carbon steel. From the mechanical property perspective, the AISI 304 stainless steel exhibits a maximum hardness of 215 HBW, a minimum of 0.2% proof strength with a value of 190 MPa, a minimum tensile strength of 500-700 MPa, an elongation after fracture of 45 long min and impact energy of 100 J. In this article, the experiments conducted by (El-Bahloul et al., 2015) were utilized to verify the proposed method of fuzzy AHP-MOORA but the AISI 304 stainless steel was utilized because of the important characteristics as follows: First, the material exhibits outstanding forming features. This means that the intermediate heat-softening process is unnecessary to achieve success in drawing it. Second, it exhibits good retention of desirable properties. An instance is the ability to retain toughness when using cryogenic temperatures. Thirdly, it is resistant to oxidizing acids, permitting easy cleaning and sterilization. The Applications of this material include heat exchangers, fasteners and flange production, chemical containers and automobiles as well as aerospace components, among others. A summary of the phases of the friction drilling process is given in Fig.1.

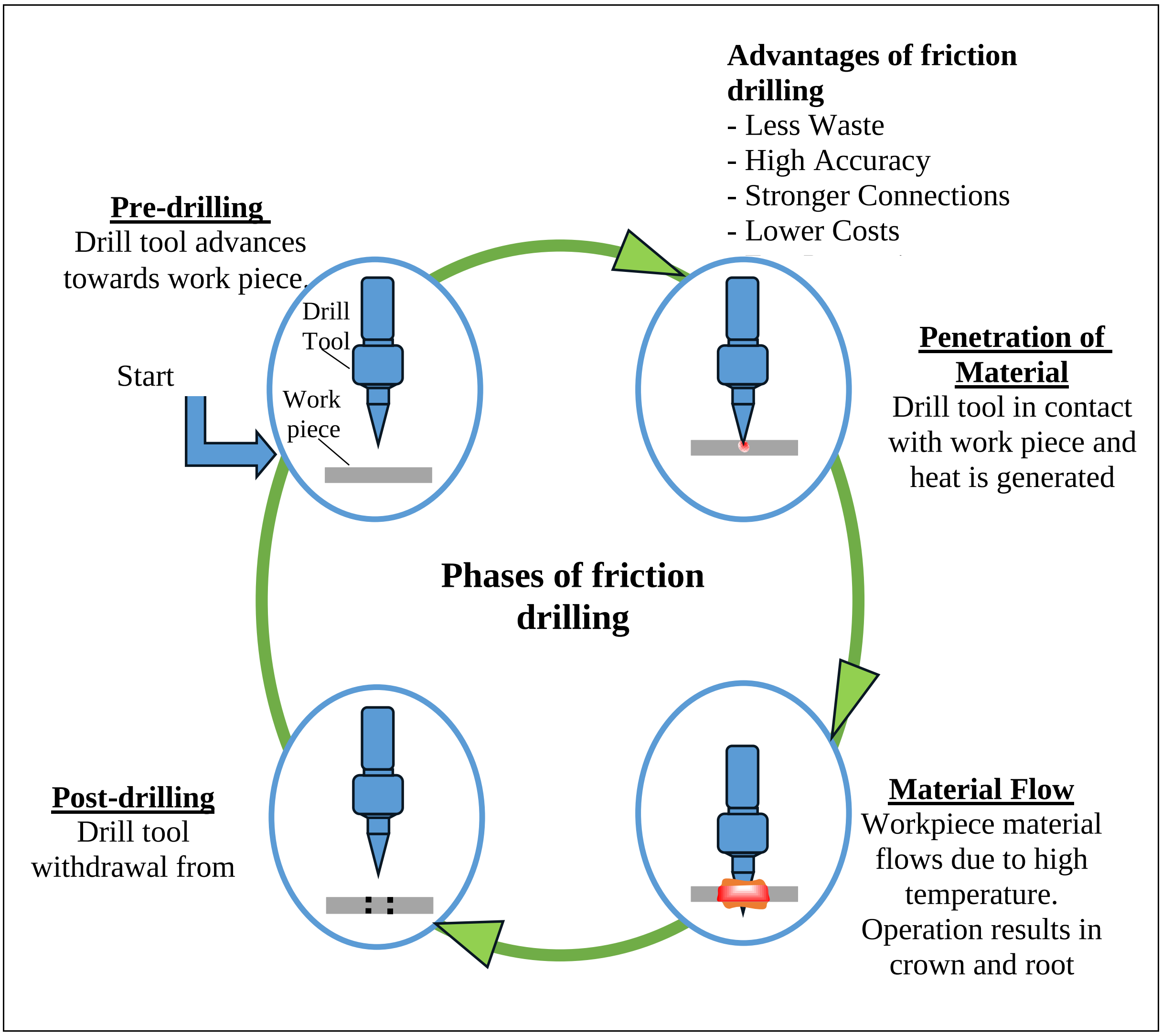

Fig.1. Phases of friction welding

3.3. Methods

Instead of the dominant Taguchi-based approaches in the literature, this section suggests a new drilling selection model, which combines a classification scheme for parameters, a fuzzy analytic hierarchy process, and the MOORA (multi-objective optimization on the basis of ratio analysis). The parameters associated with the thermal friction drilling process are first segregated into three main levels, namely target, criterion and parameter. It results in a pair-wise comparison scheme, which reveals diverse options and their associated criteria. This provides weights of parameters which can be in fuzzy numbers or crisp numerical values. The results are used in a matrix of responses for options to the objectives that apply the proportions. The emphasis is that crisp numerical values are insufficient during the analysis of insufficient information from the thermal friction drilling process. This considered the limitations of the previous Taguchi-based optimization process such as reported in (Nwankiti and Oke , 2022). To deepen the researcher's understanding of the flow process for this research, Fig. 2 is provided.

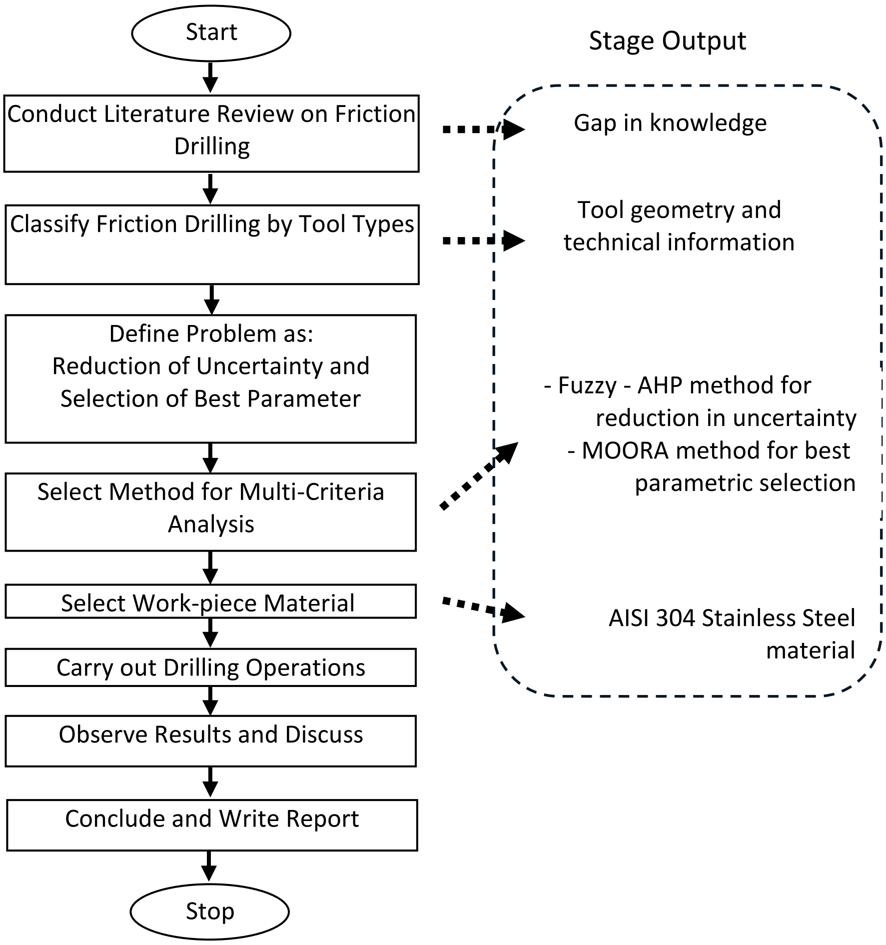

Fig. 2. Flowchart of the research process

In Fig. 2, there is a flow of information from the conduct of the literature review to the conclusion of the work with the writeup. Each major component step on the left hand side of Fig. 2 is matched with the expected outcome at the phase of the figure.

3.3.1. Fuzzy AHP

Here, an explanation is given of the fuzzy analytic hierarchical process that is suitable to assess the weights of criteria for the thermal friction drilling process. The foundation of the fuzzy AHP is the analytic hierarchy process that is developed from the idea of a pairwise comparison matrix. The classical type has a scale of importance, which usually contains three parts. The first part contains the first five odd numbers of the number system. These are 1, 3, 5, 7 and 9. Each of these odd numbers has a description of importance whose strength graduates from the least odd number to the highest. In this particular case, the descriptions from 1 to 9 are "equal importance", moderate importance", "strong importance", "very strong importance", and "extreme importance", for 1, 3, 5, 7 and 9, respectively. The second part of the scaling system is a single description named "intermediate values", to which four values", namely 2, 4, 6 and 8 are assigned. The third part of the scaling scheme is the assigned values for inverse comparison. Thus consider the inverses of each of the first five odd numbers earlier mentioned and the values assigned are 1/3, 1/5, 1/7, and 1/9. The usefulness of the scale of comparative importance, separated into three parts, is to aid the comparison of alternatives or criteria. In summary, for the scale of comparative importance representing the fuzzy AHP, there are two groups of values. These are crisp numerical values such as 1,3,5, 7 and 9. In operationalizing the fuzzy scheme, the crisp numerical numbers are converted into fuzzy numbers. It is worth noting that using the fuzzy AHP method experts who are represented by the present authors assign numbers to alternatives.

Furthermore, using a fuzzy system for the analysis of the thermal friction process requires an understanding of various terms. Fuzzification is a key term in this respect. The meaning is the mechanism to convert linguistic terms into membership functions. The term membership function could relate to several types. However, the type used in the present study is the triangular membership function. This membership function derives its name from its shape, which is triangular. It is important to note that there are other membership functions but these are not used in the present study. Examples of these membership functions are the trapezoidal and bell-shaped membership functions. Generally, the fuzzy value is represented by $\mu_{\overline{A}}(x) = \overline{A} = (1,2,3)$ where the "(1, 2, 3)" is called the fuzzy number. However, these numbers are associated with the membership function, and they are the lower, middle and upper parts of the triangle containing 1,2 and 3, respectively. Now, referring to the scale of comparative importance mentioned earlier, the crisp numbers 1, 3, 5, 7, 9 will each have a fuzzy number where these crisp numbers become the middle numbers. However, the exception is the case of crisp numerical numbers 1 and 9 whose fuzzy numbers are (1, 1, 1) for the crisp number 1 while the fuzzy number for the crisp 9 is (9, 9, 9). Apart, all other crisp numerical numbers 3,5 and 7 are individual middle values of the fuzzy numbers that they represent. It means that the fuzzy number for crisp numerical number 3 is (2, 3, 4) where 3 is at the centre. Also, for crisp values 5 and 7, the fuzzy numbers are (4, 5, 6) and (6, 7, 8) respectively. From the stage, a pairwise comparison matrix is formed consisting of a crisp numeric value. However, these values should be replaced by a fuzzy number. In the pairwise comparison matrix, the reciprocal values are not converted into fuzzy numbers in the way the pairwise comparison matrix is initially displayed. However, to achieve this transformation Equation (1) is utilized. Thus, the fuzzy number is converted into its reciprocal, Equation (1).

To get the fuzzy numbers for the reciprocals

$$\overline{A}^{-1} = (l, m, u)^{-1} = \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right) \tag{1}$$

Using Fuzzy AHP proposed by Buckley (1985), the geometric mean is used to calculate the weights, Equation (2).

$$\overline{A}_1 \otimes \overline{A}_2 = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 * l_2, m_1 * m_2, u_1 * u_2)^{-1} \tag{2}$$

At this stage, the matrix obtained is the fuzzified pairwise comparison matrix. However, further computations will warrant the use of the geometric mean method by Buckley, developed in 1985 to evaluate weights. Here, the geometric mean is used to calculate the weights. Next, the researcher computes the fuzzy geometric mean value, Equation (2). This Equation (2) is used to multiply two fuzzy numbers. Here, the lower points of the number are multiplied by another lower point of the second fuzzy number. Also, the middle point of one fuzzy number is multiplied by the middle point of the other fuzzy number. Likewise, the upper point of a fuzzy number is multiplied by the upper point of the other number. The multiplied fuzzy member is shown on the right-hand side of Equation (2). Next, the geometric mean values are calculated by Equation (3).

To find the reciprocal of the fuzzy number, recall Equation (3)

The reciprocal of the geometric mean summation,

$$\overline{x}_i = \overline{r}_i \oplus (\overline{r}_1 \oplus \overline{r}_2 \oplus \ldots \overline{r}_n)^{-1} \tag{3}$$

Also, the fuzzy weight for every criterion is calculated using Equation (4). The right-hand side of Equation (4) reveals that all the fuzzy geometric mean need to be added. Multiplying the geometric mean values by the reciprocal of the geometric mean summation gives Equation (4): Fuzzy weights for every criterion are calculated as $\overline{w}_i$

$$\overline{w}_i = \overline{r}_i \otimes (\overline{r}_1 \otimes \overline{r}_2 \otimes ... \overline{r}_n)^{-1} \tag{4}$$

Then Equation (5) is for achieving this purpose of adding two fuzzy numbers. Simply, the lower values in each fuzzy number are added. The middle values are also added while the upper values of the fuzzy numbers are added. This gives the summation of two fuzzy numbers. In Equation (5), the reciprocal of the sum is actualized. However, it is known that to find the reciprocal of fuzzy numbers, each geometric mean value is multiplied by the reciprocal of the geometric mean summation. The formula for adding two fuzzy numbers

$$\overline{A}_1 \oplus \overline{A}_2 = (l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{5}$$

On solving this one will obtain the fuzzy numbers. Afterwards, the obtained fuzzy weights may now be used as the input to the MOORA method. Alternatively, it could be converted into crips numerical values by defuzzification using the centre of area, Equation (6). Defuzzyfying the fuzzy weights to obtain crisp numeric values using the Centre of Area (COA) method, Equation (6).

$$w_i = \left(\frac{l + m + u}{3} \right) \tag{6}$$

Then the values obtained from the subtraction are ranked. The ranks are then used to obtain the top three experimental trials. Here, the lower, middle and upper values of the fuzzy numbers are added and divided by 3. The final answer is then used in section 3.3 where the MOORA method is explained.

3.3.2. Moora Method

Here, the MOORA method is the second selection method introduced, which compliments the output of the fuzzy AHP method. The criteria considered are the same utilized for the fuzzy AHP method, which are AF, RF, DE, RE and BL. Then these criteria should be sub-categorized into beneficial and non-beneficial criteria. Furthermore, the weights from the fuzzy AHP method and afterwards, the multiplication of the normalised matrix and the associated weights are made. Accordingly, the sum of all beneficial criteria is obtained and the sum of non-beneficial criteria is also calculated.

Step 1: Normalize the decision matrix, Equation (7)

$$X = \begin{bmatrix} x_{11} & . & . & . & x_{1n} \\ . & . & & & . \\ . & & . & & . \; . \\ . & & & . & . \\ x_{m1} & . & . & . & x_{mn} \end{bmatrix} \tag{7}$$

The equation to normalize the decision matrix is Equation (8)

$$x_{ij}^{*} = \frac{x_{ij}}{\left[\sum_{i=1}^{m} x_{ij}^{2}\right]^{\frac{1}{2}}} \tag{8}$$

where j = 1,2,…,n

Step 2: Estimation of Assessment values, Equation (9)

$$y_i = \sum_{j=1}^{g} w_j x_{ij}^{*} - \sum_{j=g+1}^{n} w_j x_{ij}^{*} \tag{9}$$

where j = 1,2,…,n

Equation (9) is interpreted as the sum of all the beneficial attributes – the sum of all the non-beneficial attributes

4. RESULTS AND DISCUSSION

In this section, explanations are given on the multicriteria fuzzy AHP-MOORA method to optimize the thermal friction process. Consequently, Table 1 reveals the inputs and outputs, obtained from (El-Bahloul et al., 2015). By observing Table 1 see Table 3 of (El-Bahloul et al., 2015) and closely examining the columns for AF, RF, DE, RE and BL for experiments 2, 11 and 18, there are no values indicated since the experiments were not executed successfully as the drill bit broke off during experiments. To progress with computations, the analyst needs to decide between two options available. The first option is that based on other data of the mentioned parameters (i.e. AF, RF, DE, RE and BL), the Monte Carlo simulation tool could be used to predict the missing numbers. The second approach is to eliminate the missing experiments and then reduce the 18 experiments to 15 experiments. Since both approaches are acceptable and the present authors are careful not to distort the data, the latter approach is adopted where the elimination of the three outliers is made to work with 15 experiments.

The significance of the thermal friction input parameters is to reflect the parameters that most influence the thermal friction process. These act through the heat conduction process. These, however, functions based on the temperature of the AISI 304 stainless steel considered in the work. Then, the input parameters permit the use of data from the process for further usage.

Moreover, the output parameters have a feedback connection loop with the input. More specifically defined, the output parameters for the thermal friction process refer to those elements of the thermal friction process whose values are passed out from the processing of the input parameters. The continuous production of the output is approved by a system controller that compares inputs to outputs through a feedback loop. Of importance to the engineer is to understand what was done to the three points at which the experiment failed because of the broken tool during the thermal friction process. Notice that in the initial table used by (El-Bahloul et al. ,2015) (which is not presented in the present work), there are 18 experimental trials shown. Then, afterwards, 15 experimental trials were shown, which justifies that at three points the experiments failed. Table 2 shows the AHP method, used to achieve weights, referring to the magnitude of importance of an output when related to other outputs.

Table 1. Process parameters developed by Taguchi and experimental S/N ratios obtained at each stage of the experiment

S/No.	d (mm)	B (degree)	FCAR (%)	T (mm)	FR (mm/min)	RS (rpm)	AF	RF	DE	RE	BL
1	5.4	30	50	1	60	2500	1	1	1	0.43	0.22
2	5.4	30	75	3	140	1500	*	*	*	*	*
3	5.4	45	50	2	100	1500	0.37	0.47	0.39	0.37	0.47
4	5.4	45	100	1	140	3500	0.89	0.73	0.6	1	0
5	5.4	60	75	2	60	3500	0.57	0.46	0.28	0.24	0.48
6	5.4	60	100	3	100	2500	0.05	0.03	0.19	0.4	0.6
7	7.3	30	100	1	100	1500	0.93	0.79	0.49	0.57	0.22
8	7.3	30	100	2	60	3500	0.64	0.69	0.19	0.05	0.62
9	7.3	45	50	3	140	3500	0.24	0.38	0.34	0.24	0.81
10	7.3	45	75	2	100	2500	0.48	0.55	0.54	0.21	0.6
11	7.3	60	50	3	60	1500	*	*	*	*	*
12	7.3	60	75	1	140	2500	0.88	0.73	0.44	0.76	0.16
13	9.2	30	50	2	140	2500	0.51	0.33	0.34	0.07	0.78
14	9.2	30	75	3	100	3500	0.39	0	0	0	1
15	9.2	45	75	1	60	1500	0.91	0.73	0.24	0.32	0.33
16	9.2	45	100	3	60	2500	0	0.23	0.03	0.09	0.99
17	9.2	60	50	1	100	3500	0.99	0.56	0.37	0.26	0.45
18	9.2	60	100	2	140	1500	*	*	*	*	*

*At experimental trials 2, 11 and 18, the experiment was not executed successfully as the drill bit broke off, hence the next table shows the input and output values with the three experimental trials removed.

Table 2. AHP scoring approach (scale of relative importance)

Intensity of value	Fuzzy	Interpretation
1	1, 1, 1	Requirements i and j are of equal value
3	2, 3, 4	Requirement i has a slightly higher value than j
5	4, 5, 6	Requirement i has a strongly higher value than j
7	6, 7, 8	Requirement i has a very strongly higher value than j
9	9, 9, 9	Requirement i has an absolutely higher value than j
2	1, 2, 3	Intermediate values
4	3, 4, 5	Intermediate values
6	5, 6, 7	Intermediate values
8	7, 8, 9	These are intermediate scales between two adjacent judgments
Reciprocals		If requirement i has a lower value than j

In essence, the criteria or standard which is used in the work are presented in Table 2. Interestingly, the magnitude of importance of these parameters are qualitative values, i.e. not quantitative or concrete. So this approach is used to make them quantitative by attaching fuzzy values to them. Consequently, Tables 2, 3 and 4 help the researcher to fuzzify and quantify the importance that is attached to these values.

Table 3. Pair-wise comparison matrix

Parameters	AF	RF	DE	RE	BL
AF	1	1	1	1	1/3
RF	1	1	1	1	1/3
DE	1	1	1	1	1/3
RE	1	1	1	1	1/3
BL	3	3	3	3	1

Table 4. Corresponding fuzzy numbers

Parameters	AF	RF	DE	RE	BL
AF	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1	1/3
RF	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1	1/3
DE	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1	1/3
RE	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1	1/3
BL	2, 3, 4	2, 3, 4	2, 3, 4	2, 3, 4	1, 1, 1

To explain, Table 3 shows the pairwise comparison matrix while Table 4 shows the corresponding fuzzy members that were obtained from Table 2. Then, the fuzzy pairwise comparison matrix is shown in Table 5. The fuzzy geometric means are obtained in Table 6.

Table 5. Fuzzified pair-wise comparison matrix

Parameters	AF	RF	DE	RE	BL
AF	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1	1/4, 1/3, 1/2
RF	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1	1/4, 1/3, 1/2
DE	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1	1/4, 1/3, 1/2
RE	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1	1/4, 1/3, 1/2
BL	2, 3, 4	2, 3, 4	2, 3, 4	2, 3, 4	1, 1, 1

Table 6. Fuzzy numbers with their respective geometric mean

Parameters	AF	RF	DE	RE	BL	Fuzzy geometric mean value $\bar{r}_i$
AF	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1	¼, 1/3, 1/2	0.707,0.760,0.841
RF	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1	¼, 1/3, 1/2	0.707,0.760,0.841
DE	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1	¼, 1/3, 1/2	0.707,0.760,0.841
RE	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1	¼, 1/3, 1/2	0.707,0.760,0.841
BL	2, 3, 4	2, 3, 4	2, 3, 4	2, 3, 4	1, 1, 1	2,3,4

Furthermore, a summation of the fuzzy geometric means with values is shown. After this, the reciprocal of the geometric mean summation is obtained, in Table 7, Now, in Table 8, the weights have been obtained.

Table 7. Fuzzy geometric mean and Fuzzy weights obtained

Fuzzy geometric mean value $\bar{r}_i$	Fuzzy weights $\bar{w}_i$
0.707,0.760,0.841	0.096,0.126, 0.174
0.707,0.760,0.841	0.096,0.126, 0.174
0.707,0.760,0.841	0.096,0.126, 0.174
0.707,0.760,0.841	0.096,0.126, 0.174
2,3,4	0.272, 0.497, 0.829

Table 8. Discretized fuzzy weights

Fuzzy weights $\bar{w}_i$	Weights $\bar{w}_i$
0.096,0.126, 0.174	0.132
0.096,0.126, 0.174	0.132
0.096,0.126, 0.174	0.132
0.096,0.126, 0.174	0.132
0.272, 0.497, 0.829	0.533

In the present case, four non-beneficial criteria and a beneficial criterion have been used to classify the output parameters. It means that the researchers want to minimize four outputs and maximize one output. Notably, these four non-beneficial criteria have the same weights. Here, the only beneficial criterion is the behind length, which is to be maximized. It means that it affects the overall selection in a very significant way compared to the other output values. So, now, the consideration of the MOORA method of multiple criteria decision-making is made. Notice that the weights obtained from the AHP are shown in Table 9.

Table 9. Output parameters at the several experimental trials as well as their weightage on the scale of importance and their status in terms of being beneficial or non-beneficial

Weightage	0.132	0.132	0.132	0.132	0.533
Status	Non Beneficial	Non Beneficial	Non beneficial	Non beneficial	Beneficial
	AF	RF	DE	RE	BL
1	1	1	1	0.43	0.22
2	0.37	0.47	0.39	0.37	0.47
3	0.89	0.73	0.6	1	0
4	0.57	0.46	0.28	0.24	0.48
5	0.05	0.03	0.19	0.4	0.6
6	0.93	0.79	0.49	0.57	0.22
7	0.64	0.69	0.19	0.05	0.62
8	0.24	0.38	0.34	0.24	0.81
9	0.48	0.55	0.54	0.21	0.6
10	0.88	0.73	0.44	0.76	0.16
11	0.51	0.33	0.34	0.07	0.78
12	0.39	0	0	0	1
13	0.91	0.73	0.24	0.32	0.33
14	0	0.23	0.03	0.09	0.99
15	0.99	0.56	0.37	0.26	0.45

Also, the status of each of the outputs in the beneficial or non-beneficial contexts is known. Moreover, the values of successful experiments are also shown. Therefore, the first step of the MOORA is applied here. With only two steps in its application, the MOORA method is simple to use as a decision method based on multicriteria principles. Thus, in Table 10, step 1 of the MOORA method is conducted, which made the decision matrix to be normalized. This is converting Table 9 to Table 10 by using a series of operations.

Table 10. Normalized values of the decision matrix

x_{ij}^*	AF	RF	DE	RE	BL
1	0.3830968	0.4447916	0.5960623	0.2602907	0.096162
2	0.1417458	0.2090521	0.2324643	0.2239711	0.205436
3	0.3409561	0.3246979	0.3576374	0.6053273	0
4	0.2183652	0.2046041	0.1668974	0.1452786	0.209807
5	0.0191548	0.0133437	0.1132518	0.2421309	0.262259
6	0.3562800	0.3513854	0.2920705	0.3450366	0.096162
7	0.2451819	0.3069062	0.1132518	0.0302664	0.271001
8	0.0919432	0.1690208	0.2026612	0.1452786	0.354050
9	0.1838865	0.2446354	0.3218736	0.1271187	0.262259
10	0.3371252	0.3246979	0.2622674	0.4600488	0.069936
11	0.1953794	0.1467812	0.2026612	0.0423729	0.340937
12	0.1494077	0	0	0	0.437098
13	0.3486181	0.3246979	0.143055	0.1937047	0.144242
14	0	0.1023021	0.0178819	0.0544795	0.432727
15	0.3792658	0.2490833	0.2205431	0.1573851	0.196694

This was actualized by adopting the relevant equations from the methodology aspect of the work. Here, the squares of the values are obtained, the sum is obtained and the square root of the sum is also obtained. Then each of the individual values is divided by the value so obtained. Table 11 distinguishes the sum of the non-beneficial attributes from those of the beneficial attributes.

Table 11. Multiplication of the normalized matrix with their respective weights

W^*x_{ij}	AF	RF	DE	RE	BL
1	0.0505688	0.0587125	0.0786802	0.0343584	0.051254
2	0.0187104	0.0275949	0.0306853	0.0295642	0.109497
3	0.0450062	0.0428601	0.0472081	0.0799032	0
4	0.0288242	0.0270077	0.0220305	0.0191768	0.111827
5	0.0025284	0.0017614	0.0149492	0.0319613	0.139784
6	0.047029	0.0463829	0.0385533	0.0455448	0.051254
7	0.032364	0.0405116	0.0149492	0.0039952	0.144443
8	0.0121365	0.0223107	0.0267513	0.0191768	0.188708
9	0.024273	0.0322919	0.0424873	0.0167797	0.139784
10	0.0445005	0.0428601	0.0346193	0.0607264	0.037276
11	0.0257901	0.0193751	0.0267513	0.0055932	0.181719
12	0.0197218	0	0	0	0.232973
13	0.0460176	0.0428601	0.0188833	0.025569	0.076881
14	0	0.0135039	0.0023604	0.0071913	0.230644
15	0.0500631	0.032879	0.0291117	0.0207748	0.104838

Thus, the values to be minimized are subtracted from those to be maximized. However, at first, the weights are multiplied by the normalized values and the sum is found. This is done for each experimental trial. In one experimental trial, all the values, which have been normalized are multiplied by their weights and the sum is found for the beneficial and the non-beneficial parameters. Consequently, the subtraction is done as shown in Table 12.

Table 12. Beneficial and the Non-beneficial criteria (Yi) at each experimental trial

Expt.	Non- Beneficial	Beneficial	(Beneficial) – (Non-beneficial)
1	0.2223	0.0513	-0.1711
2	0.1066	0.1100	0.0029
3	0.2150	0.0000	-0.2150
4	0.0970	0.1118	0.0148
5	0.0512	0.1398	0.0886
6	0.1775	0.0513	-0.1263
7	0.0918	0.1444	0.0526
8	0.0804	0.1887	0.1083
9	0.1158	0.1398	0.0240
10	0.1827	0.0373	-0.1454
11	0.0775	0.1817	0.1042
12	0.0197	0.2330	0.2133
13	0.1333	0.0769	-0.0564
14	0.0231	0.2306	0.2076
15	0.1328	0.1048	-0.0280

According to the results obtained from the MOORA multi-objective method, the top three combinations of the experimental trials are 12, 14 and 8. They are depicted in Table 14. Furthermore, in this work, the data from (El-Bahloul et al.,2015) was used to validate the developed fuzzy AHP-MOORA method. However, the results obtained from the application of the Taguchi-based method of (El-Bahloul et al., 2015) were used to verify the present model. The motivation is that (El-Bahloul et al., 2015) presented a multi-performance characterization index with which we can compare our results. Out of the 15 ranks of experiments in both articles, experimental trials 2, 4 and 9 with ranks of 9, 8 and 7, respectively are the same. This means that 20% of ranks in both articles are the same Table 13. The differences in the results may be largely due to the introduced MOORA method which gives improved performance to our current model.

Table 13. The difference between the beneficial and non-beneficial is ranked

	Present study		Verification study (El-Bahloul et al., 2015)		
Expt.	**Y_i**	**Rank**	**MPCI***	**Rank**	**Comment**
1	-0.1711	14	0.7610	1	Different
2	0.0029	9	0.4860	9	Same
3	-0.2150	15	0.6340	3	Different
4	0.0148	8	0.4990	8	Same
5	0.0886	5	0.2440	14	Different
6	-0.1263	12	0.6640	2	Different
7	0.0526	6	0.4300	11	Different
8	0.1083	3	0.4690	10	Different
9	0.0240	7	0.5000	7	Same
10	-0.1454	13	0.6180	5	Different
11	0.1042	4	0.5000	7	Different
12	0.2133	1	0.3500	12	Different
13	-0.0564	11	0.6030	6	Different
14	0.2076	2	0.3290	13	Different
15	-0.0280	10	0.6250	4	Different

MPCI – Multiple performance characteristic index

Table 14. Top three optimal experimental trials according to the MOORA MCDM

Expt. Trial	AF	RF	DE	RE	BL
12	0.39	0	0	0	1
14	0	0.23	0.03	0.09	0.99
8	0.24	0.38	0.34	0.24	0.81

5. CONCLUSIONS

The effectiveness of the drilling process while machining stainless steel is maintained through the choice of an appropriate thermal drilling process. However, over the years, several studies have evolved by studying the thermal friction concept of steel. (Miller et al., 2005) introduced the idea of thermal friction drilling and related it to the distortions of the microstructure of the steel. Although the AISI 1020 steel and AISI 4130 steel were selectively studied, the variations in their hole measurement characteristics such as the diameter of the support for the bushing, the average bushing and average boss extruded heights below and above the sheet and the hole diameter make it compelling to study the AISI 304 stainless steel, which is the focus of the present study. (Chow et al., 2008) focused on the attributes of AISI 304, through a Taguchi optimization route, using the sintered carbide drill. Though the material studied in this article and the reviewed work is the same, i.e. AISI 304, the difference between the two articles is the complete absence of a mechanism to evaluate the uncertainty and imprecision in the experiments conducted in the reviewed article and the gap is bridged in the present study.

More importantly, the following conclusions are valid from the results obtained in this study:

1. The use of the fuzzy AHP-MOORA method to select parameters of the thermal friction drilling process is feasible in the context of demonstrating this using the AISI 304 stainless steel material.
2. Following the analysis of the inputs and outputs for the friction drilling of AISI 304, an appropriate drill geometry was established and uncertainty as well as imprecision in the experiment were reduced. Accordingly, experimental count 12 is ranked the best. The second and third experimental counts are 14 and 18, respectively. However, experiment 12 revealed a difference of 0.2133 for the beneficial and non-beneficial components of the process. The optimal inputs are d (7.3mm), b (60°), FCAR (75%), t (1mm), FR (140mm/min) RS (2500rpm). But the outputs are AF (0.88), RF (0.73), DE (0.44), RE (0.76) and BL (0.16).
3. By implementing the optimal drilling parameters, the friction drilling process was capable of generating a bush length which is 16% of the work piece thickness.

However, future studies may engage in merging other methods with the fuzzy AHP-MOORA to obtain a more robust performance of the material under the thermal friction drilling process. Candidate methods for the merger may be TOPSIS and VIKOR multicriteria methods.

Abbreviations/Notations

RE	Roundness error
RF	Radial force
BL	Bushing length
AF	Axial force
FCAR	Friction contact area ratio
t	Workpiece thickness
FR	Feed rate
RS	Rotational speed
DE	Dimensional error
d	tool cylindrical region diameter
β	Frictional angle
MPCI	Multiple performance characteristic index

6. REFERENCES

Albarbary Y.E., Afify R., Mansour E.H., Mahmoud T.S., Khedr M. 2022, The effect of pre-drilling on the characteristics of friction drilled A356 cast aluminum alloy, Journal of Manufacturing Processes, Vol. 82, pp. 646-656. https://doi.org/10.1016/j.jmapro.2022.08.040.

Alinezhad A. and Khalili J., 2019, MOORA method, in New Methods and Applications in Multiple Attribute Decision Making, pp. 81-85. https://doi.org/10.1007/978-3-030-15009-9-11.

Backar A., Elhofy M., Nassef G., 2020, Finite elements modelling of friction stir welding, International Journal of Advanced Science and Technology, Vol. 29, pp. 29-43 .

Baksa T., Kroupa T., Hanzi P., Zetek M., 2015, Durability of cutting tool during machining of very hard and solid material, Procedia Engineering, Vol. 100, pp.1414-1423.https://doi.org/10.1016/j.proeng.2015.01511.

Baraheni M., Bami A.B., Alaei A., Amini S. 2021, Ultrasonic-assisted friction drilling process of aerospace aluminium alloy (AA7075): FEA and experimental study, International Journal of Lightweight Materials and Manufacturing, Vol . 4, pp. 315-322.

Belov D. S., Klauch D.N., Blinkov I.V., Laptev I. A. and Demirov A.P., 2024, Durability of cutting tools with deposited ceramic-metal coatings (Ti, Al) N-Cu and (Ti, Al) N-Ni duraing turning and milling of steels, Functional Coatings and Surface Treatment, Vol. 15, pp.752-752.

Bilgin M.B., Gok K and Gok A., 2015, Three-dimensional finite element model of friction drilling process in hot forming processes, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, Vol. 231, No. 3. https://doi.org/10.1177/0954408915614300.

Bilgin M.B., Gok K., Gok A, 2017, Three dimensional finite element model of friction drilling process in hot forming processes, Procedures of Institution of Mechanical Engineering, Vol. 231, pp. 548-554.

Boopathi M., Shankar S., Manikandakuman S., Ramesh R., 2013, Experimental investigation of friction drilling on brass, aluminium and stainless steel, Procedia Engineering, Vol. 64, pp. 1219-1226.

Brauers W.K.M., Zavadskas E.K., 2006, The MOORA method and its application to privatization in a transition economy, Control and Cybernetics, Vol. 35, No. 2, pp. 445-469.

Chityal N., Sapkal S. 2022, Performance analysis of GA, PSO and JA for determining the optimal parameters in friction drilling process, Engineering Science and Technology, an International Journal, Vol. 35, Article 101246. https://doi.org/10.1016/j.jestch.2022.101246.

Chow H.-M, Lee S.M., Yang L.D., 2008, Machining characteristic study of friction drilling on AISI 304 stainless steel. Journal of Materials Processing Technology, Vol. 207, No. 1-3, pp. 180-186. https://doi.org/10.1016/j.matprotec.2007.12.064.

Datta S., Saliu N., Mahapatra S., 2013, Robot selection based on grey-MULTIMOORA approach, Grey Systems: Theory and Application, Vol. 3, No. 2, pp. 201-232. https://doi.org/10.1108/GS-05-2013-0008.

Demar Z and Ozek C., 2014, Investigate the effect of pre-drilling in friction drilling of AA7075-T651, Materials and Manufacturing Processes, Vol. 29, No. 5, pp. 593-599. https://doi.org/10.1080/1046914.2014.892986.

Dwivedi S.K., Dwivedi A., 2018, Application of MOORA and WSM method for supplier selection in manufacturing, International Journal of Advance Research, Ideas and Innovations in Technology, Vol. 3, No. 7, pp. 114-117.

El-Bahloul S.A., El-Shourbagy H.E., El-Midany T.T. 2015, Optimization of thermal friction drilling process based on taguchi method and fuzzy logic technique, International Journal of Science and Engineering Applications, Vol. 4, No. 2, pp. 55-59.

Emovon I., Okpako, O.S, Edijokpa E., 2021, Application of fuzzy MOORA method in the design and fabrication of an automated hammering machine, World Journal of Engineering, Vol. 18, No. 1, pp. 37-49. https://doi.org/10.1108/WJE-07-2020-02550.

Fadli S., Imtihan K., 2019, Implementation of MOORA method in evaluating work performance of honorary teachers, SinkrOn : Jurnal dan Penelitian Teknik Informatika, Vol. 4, No. 1, pp. 128-135. https://doi.org/10.33395/sinkron.v4i1.10192.

Gadakh V.S., 2011, Application of MOORA method for parametric optimization of milling process, International Journal of Applied Engineering Research, Vol. 1, No. 4, pp. 743-758.

Hamzawy N., Mahmoud T.S., El-Mahallawi I., Khalifa T. and Khedr M., 2023, Optimisation of thermal drilling parameters of 6082 Al-Alloy based on response surface methodology, Arabian Journal for Science and Engineering, Vol. 48, pp. 12001-12014.

Karakoç H., Bilgin M., Karabulut Ş. 2024, Study on the friction drilling behaviors and tribological properties of aluminum matrix composites, Materials Today Communications, Vol. 38, Article 108086. https://doi.org/10.1016/j.mtcomm.2024.108086.

Kumar R. and Hymes N.R.J., 2019, Influence of rotational speed on mechanical features of thermally drilled holes in dual-phase steel, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 233, No. 5, pp. 1588-15693. https://doi.org/10.1177/0954405418805601.

Manokhin A.S., Klimenko S. A., Beresnev V.M., Stolbovoy V.A., Klimenko S.A., Melniichuk Y.A., Naidenko A. G., Ryzhov Y.E., Depu L., Honshun W., 2020, Wear rate of PcBN cutting tools equipped with nanolayered protective coatings, Tools, Powders, Pastes, Vol. 42, pp. 423-431.

Matawale C.R, Datta S, Mahapatra S.S. 2016, Supplier selection in agile supply chain: Application potential of FMLMCDM approach in comparison with fuzzy-TOPSIS and fuzzy-MOORA, Benchmarking: An International Journal, Vol. 23, No. 7, Pp. 2027-2060, https://doi.org/10.1108/bij-07-2015-0067.

Miller S.F., Blau P.J., Shih A.J., 2005, Microstructural alterations associated with friction drilling of steel, aluminium and titanium, Journal of Materials Engineering and Performance, Vol. 14, No. 5, pp. 647-653.

Nwankiti U.S. and Oke S.A. 2022, Thermal friction drilling process parametric optimization for AISI 304 stainless steel using an integrated taguchi-pareto–grey wolf-desirability function analysis optimization technique, Indonesian Journal of Industrial Engineering & Management, Vol. 3, No. 3, pp. 210-223.

Ozher L. and Dogru N., 2013, An experimental investigation of hole geometry in friciton drilling, Materials and Manufacturing Processes, Vol. 28, No. 4, pp. 470-475. https://doi.org/10.1080/10426914.2012.746699.

Patel J.D., Maniya K.D., 2015, Application of AHP/MOORA method to select wire cut electrical discharge machining process parameter to cut EN31 alloys steel with brass wire, Materials Today: Proceedings, Vol. 2(4-5), pp. 2496-2503.https://doi.org/10.1016/J.Matpr.2015.07.193.

Rane S., Potdar P.R., Rane S., 2021, Data-driven fleet management using MOORA: A perspective of risk management, Journal of Modelling in Management, Vol. 16, No. 1, pp. 310-338. https://doi.org/10.1108/jm2-03-2019-0069.

Ranjith R., Nalin S., Kumar V., 2022, Integrated MOORA-ELECTRE Approach for solving multi-criteria decision problems, World Journal of Engineering, Vol. 19, No. 4, Pp. 510-521. https:doi.org/10.11008/wje-12-2020-0656.

Stockburger E., Zhang W., Wester H., Rosenbuse D., Behren B.-A., 2023, Process analyses of friction drilling using the smoothed particle galerkin method, International Journal of Material Forming, Vol. 16, article 14.

Thakkar J.J., 2021, Multi-objective optimization on the basis of ratio analysis method (MOORA). In: Multicriteria Decision Making Studies in Systems, Decision and Control, Article 336, Springer, Singapore. https://doi.10.1007/978-981-33-4745-8-11.

Urbikain G., Perez J.M., 2016, Combination of friction drilling and form tapping processes on dissimilar materials for making nutless joints, Proceedings of Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 232, No. 6 https://doi.org/10.1177/0954405416661002.

Volkhonski A.O., Blinkov I.V., Anikin V.N., Belov D. S., Sergevnin V.S., 2015, Hardening the hard-alloy edge tool used for cutting the tough-to-machine titanium alloys and chromium-nicked steels with multiplayered nanostructured coatings, Powder Metallurgy of Nonfererous Metals and Alloys, Vol. 56, pp. 633-641.