

Parametric Selection and Optimization for the Drilling Of AZ91 Magnesium Alloys Using the Taguchi Method Incorporating Direct and Aspect Parametric Ratios

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Abstract. *The central pursuit in drilling optimisation is to reduce, control and monitor the diverse process-oriented defects. However, in the drilling of AZ91 magnesium alloy, the optimisation approach adopted using the Taguchi technique still lacks complete capture of relevant data for the effective hole creation defect minimization. At present, the aspect ratios are completely ignored in the determination of optimal parametric settings using the factor-level response table evaluation route. This paper overcomes this shortcoming by introducing some aspect ratios into the computational framework of optimisation using the Taguchi method. Literature data regarding the drilling of AZ91 magnesium alloy was used to validate the proposed optimisation approach. The approach consists of defining the factor-level table to incorporate aspect ratio factors. Then, the orthogonal matrix, signal-to-noise ratios and the summarized signal-to-noise ratio (response) table are then declared. With the direct parameters of speed and feed considered in the literature sources for validating the method, aspect ratios were formulated to involve the ratios of speed to feed and vice-versa. Others are the square and reciprocals of speed and feed parameters. A total of eight alternatives were formulated and tested with each alternative consisting of the squares reciprocals or aspect ratios of the speed and feed parameters. Results showed that 41.67% of all the tested parameters significantly impact surface roughness during the drilling operation. These are the square and cube of feed rate, the reciprocals of the square and cube of speed and the ratio of the feed rate to speed. It is concluded that the study provides a useful route to analyzing the optimisation and performance potential of the drilling process for cost-effective drilling activities.*

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1. Introduction

Drilling is a conventional hole-making machining operation conducted on a wide range of metals [1], [2], [3], [4]. Examples of drilled metals include stainless steel

(AM60, [5]; AISI 304, [6]; AISI 1045, [7]; AISI 1045, [8]). Others are magnesium alloys (AZ91, [9]; AZ91D, [10]; AZ31, [11], [12], AZ61, [13], [14]; AZ31, [15]); and titanium aluminides [3]. Interestingly, a typical drilling process is achieved with the aid of a multiple-point cutting tool called the drill, which is mounted on the drilling machine [16]. However, the drill is connected to the spindle, which makes hundreds of revolutions per minute and it penetrates the workpiece upon contact by utilizing the force of friction, softening the contact point before penetrating it [17].

Besides, in a conventional drilling process, the most important factors that are used to assess the quality of the drilled products are usually the drilling time, burr depth (height), burr thickness and roughness [6], [7], [18]. Furthermore, these outcomes depend on inputs, which are principally the speed, feed rate and depth of cut in many drilling literature sources. However, for the magnesium AZ91 alloy, a lack of insight into the optimal input parameters at which to conduct the drilling process could lead to inefficient results characterized by longer drilling periods, more surface roughness and lower burr heights and thicknesses [19], [20]. Unfortunately, these have financial implications as longer drilling implies fewer products and more surface roughness, which can lead to more post-machining processes and wastage of materials in some cases.

At present, an attempt to capture and control this problem through the deployment of the Taguchi optimisation technique, to provide the basis for performance monitoring and improvement has proved ineffective because of the deployment of the wrong control mechanism in the factor-level table of the Taguchi method [8], [21], [22]. The present operating mechanism is to deploy the direct factors into the factor-level table and convert the information into the orthogonal matrix, which will be given out as the signal-to-noise ratio and then the average signal-to-noise ratios are formed for optimal parametric setting determination for the problem. Unfortunately, the shortcoming of using direct factors is its inability to properly capture intermediate and extreme values as ratios of factors are completely ignored in the analysis. Consequently, a more representative replacement of the direct factor as aspect ratios is required for value generation in the assessment procedure.

The latest literature on aspect ratios within the maintenance engineering area overcome the restraint of direct factors as Oke and Adekoya [23] capture the intermediate and extreme values in the Taguchi optimisation scheme using aspect ratios. With the validation of aspect ratios involving downtime index, cumulative density function and probability density function using the shipping industry's data, the competence of the aspect ratio mechanism to reveal more precise results and avoid errors in performance evaluation was demonstrated by Oke and Adekoya [23], furthermore, in a closely related report by Adegoke and Oke [24], the ratios of percentage concentration of nanofluids, feed rate and cutting velocity were calculated as aspect ratios and their feasibility in a turning situation was ascertained. However, with the aspect ratio introduction into the factor-level table of the Taguchi scheme, a detailed analysis of the drilling process and the relationship between the input and output parameters are possible and compelling.

From the foregoing, the aspect ratio-oriented Taguchi method has been established as a promising approach to achieving an efficient drilling operation. However, the associated output to use in the analysis of the method needs to be established from the literature [8]. Thus, along this line of thought, Kilickap et al. [7] to optimize the drilling operation considered surface roughness to be a primary output as well as considering the effect of input parameters like cutting speed and feed rate with surface roughness as the output [25]. Also, the effect of input parameters like the burr height, feed ratio and cutting speed was investigated by Kilickap and Huseyinoghi [6]. This shows that the burr dimensions, as well as the surface roughness, are vital parameters for determining the quality of drilled products. However, guided by additional literature sources including Berzosa et al. [18], is convincing to streamline the output to be considered in this article to surface roughness alone due to its wide usage and the restricted experimental data to surface roughness outcome in Varatharajulu et al. [26] used to validate the method proposed in this article.

Consequently, this paper aims to arrive at the optimal process parameters, yielding values of spindle speed and feed rate that will yield the desired optimal surface roughness and drilling time on magnesium AZ91 alloy using the aspect ratio-based Taguchi method. The aspect ratio is a popular method of analysis used in the forming process but has been lately adopted in maintenance [23] and turning operations [24]. It has the aim of reducing errors in the evaluation of optimal parametric settings. However, the versions of the aspect ratios were examined. But while only the aspect ratio was considered in Oke and Adekoya [23], there is no clear understanding of how squares and reciprocals of the constituent parameters of the aspect ratios in the Taguchi scheme behave. The introduction of these variations changes the landscape of the method and the possible outcomes. These new variations involving squares and reciprocals of aspect ratios are discussed in the present study.

2. Literature Review

In the present dispensation, sustainable development arises from the optimization of drilling operations resources while addressing the needs of the coming generations. From this perspective, the requirement to study more efficient optimization procedures to achieve sustainable development in drilling attains special importance. Thus, Scholars process engineers and designers are stimulated to search for improved Taguchi methodical ideas to cope with the escalating cost of manufacturing to introduce more manufacturing efficiency and possibly maintain low-cost manufacturing processes. At present, the use of the Taguchi method has received considerable attention from scholars and practitioners in engineering practice, particularly machining. Based on this, a literature review is conducted to understand the available revisions of the Taguchi method in the literature and the important gaps yet to be bridged. Thus, the following is a review of literature relevant to the present study.

2.1 Machining Literature

The optimal set of cutting parameters was found by Beranoagirre et al. [3] while conducting drilling experimental trials on ingot MoCuSi, TNB type and extruded MoCuSi. They declared that the feed per revolution and cutting speed that are preferred for machining the three gamma TiAl alloys are 0.025 mm/rev and 10–15m/min, respectively. Berzosa et al. [18] experimented on magnesium to determine the best tool needed to deliver its required surface roughness. They reported a lower value range than standard thereby limiting the effectiveness of the metal in real-life applications. The roughness of the surface of the AZ31magnesium syntactic foams was improved by Kannan et al. [4] with few abnormalities when using cryogenic machining. They declared that at an increase in volume fraction of alumina microspheres the quality of the surface degenerated by 125%. Akyüz [27] examined how the percentage of aluminium in AZ (AZ01, AZ21, AZ41, AZ61 and AZ91 containing 0 – 9% aluminium) alloys of magnesium influenced its mechanical properties. The author asserted that the large presence of aluminium in the structure of metal atoms of AZ magnesium alloys such as $\beta\text{-Mg}_{17}\text{Al}_{12}$ defines the behaviour of the alloy's mechanical properties.

Kilickap et al. [7] analyzed how the combination of variables; rate of feed, speed of cut and machine condition could affect the formation of roughness on a material surface after drilling. Their parametric results assumed and obtained show minimal variations thereby making the process economical and usable for setting input and output data. The choice of multiple criteria decision-making method was adopted by Varatharajulu et al. [26] to select the best optimal parametric variables due to their economic values and material machining enhancement. The input variables were minimized with output variables by following optimization procedures on TOPSIS and

COPRAS. They argued that the best parametric settings were obtained with a feed rate equal to 0.076 mm/rev and spindle speed equal to 4540 rpm. Furthermore, they declared that the derived quality of drilling time was achieved 3.959 higher than the normal drilling process. Rubio et al. [28] conducted the machining of arranged magnesium–titanium–magnesium metal components without cooling substance under constant values. It was noticed that input variables and geometry of the tool affected the results obtained on the surface of the drilled materials. Yazman et al. [9] machined alloys of magnesium AZ91 on a high-speed drilling machine and declared that the casting with the pressure bar of 1000 sustained its strength under tension without failure and that the speed of cut was insignificant to the rate of feed.

Roodposhti et al. [29] studied the effect of the gradual flow of magnesium AZ91 along its interface character. It was discovered that at a higher temperature, there was chemical composition adherence within the magnesium reaction with other reactants forming alloys. Gunasekaran et al. [30] applied an optimization algorithm to experiment with the machining processes of magnesium AZ91 to study the effects and responses of input and output parameters. The result signifies the rate of feed and speed of cut as optimal parameters. Yang et al. [31] used the neutral 3.5% NaCl aqueous solution to study the gradual erosion, structure formation and chemical reaction of Mg-8Li-3Zn-Al alloy. It was discovered that the alloy erodes lesser in deionized water as compared to 3.5% NaCl solution leaving Mg(OH)₂ as the final substance. Asal [32] studied the roughness of the surface after machining magnesium AZ31 using the Taguchi algorithm on experimentation data from a CNC machine. It was recorded that the best machining values for depth of cut at level 2 are 2 mm, feed rate at level 1 is 0.2 mm/rev and cutting speed at level 1 is 320 m/min. Buradagunta et al. [11] studied the influence of the rate of the intermetallic compound and cutting operation behaviour on AZ31 and AZ91 alloys. Load imbalances and reduction in force of cut were set up by increments in machining speed.

Yue et al. [33] investigated the impact of substance flow on expanding the AZ31 metal alloy model. The result showed that the ambient atmospheric pressure and warm-up temperature influenced the substance flow. Ren et al. [34] examined the overside qualities of Mg₂Sn (100). It was concluded that the status of overside qualities of both Mg and Sn stable endpoint was reached. Mahata and Sikdar [25] made the coefficient of elasticity and strength of hexagonal range Mg–Li nanowire alloy undergoes tensile and compressive stress. It was discovered that the connection between microscale material response and nanometer-scale properties could be to plan the best machining operation for the alloy. Pan et al. [36] examined the quantity of impure iron and silicon in magnesium alloys, which were degraded by low melting point heat treatment. It was observed that iron reduction in AZ31, AZ61, AM 60, AM 50 and ZK 60 affected the quantity of silicon they possess.

In Morin et al. [37], the rate of feed was influenced by thrust and torque during machine operation on Duralcan until the power was raised to 0.81. Sun et al. [38] declared

that at a constant temperature of 400°C, three structural compounds of Mg-Ce-Sr were decided while values of the two structural compounds of Ce-Sr were discovered. Ruan et al. [39] checked the likelihood of the formation of magnesium alloy during fabrication but underwater shock waves caused significant improvements in specimen solidity and extension coefficient. Kayir [40] studied the drilling performance of magnesium AZ91 alloy through Taguchi and ANOVA experimentation and concluded that the roughness of the surface around the drilled hole was greatly affected by the tool material selected. In Köklü et al. [41], the ratio of extrusion having different values was subjected to the drilling of AZ31 magnesium alloys. There was a reduction in the sharpness of the hole edge and an improvement in edge standard. Mohd et al. [42] examined speed, feed rate and drill diameter during the machining of materials to determine their impact on the surface roughness of a material. It was observed that the rate of feed and the speed should be at a minimum and maximum, respectively. Gariboldi [43] examined the machining behaviour of magnesium alloy in response to using coated HSS twist drill on a drilling machine. It was observed that the speed of spindle variation influenced the best final result of the machined product. Roodposhti et al. [29] studied the transformation of magnesium alloy AZ91 based on preventive measures it possesses against an external force. The material transformation is unaffected by high heat treatment. Shi et al. [44] investigated the contribution of input factors on the material machining behaviour whilst milling Mg alloy material. The consistent increase in the rate of feed and low speed of cut was discovered to favour the milling force whilst its effectiveness was stalled by the cutting speed. Devadharshini et al. [45] considered a machining process using aluminium 5052 metal matrix composites and three input parameters, namely the rate of feed, speed of spindle and drill bit. The machine part surface finish was improved upon using laminated HSS–TiN drill bit material.

In Table 1, a summary of important literature concerning the study area is given.

2.2 Observations and Gap

From the foregoing discussion on the literature survey, which reveals the gap in the literature, it is safe to conclude that the optimisation of the drilling process parameters while drilling magnesium AZ91 alloy and employing the variable structure aspect ratio is an interesting idea to enhance the drilling operations while using the CNC machine. As defined in this work, the variable structure aspect ratio is such that it contains the incorporation of both direct factors of speed and feed rate and the squares, cubes and their reciprocals subjected to a maximum of five factors in a formulation, considered as an alternative in this work. From this emerging research on the modified Taguchi method, it is clear that aspect ratio introduction is marked as a potential idea for the computation of optimal parametric settings for cost-effective drilling decisions.

S/N	Author(s) and year	Domain of study	Type of alloy material	Formulation parameters	Methods	Output (responses)	Results
1	Balamurugan et al. [2]	Lightweight structures	Magnesium based silicon carbide composite	Spindle feed rate, and constant depth of cut. Machining temperature	Stir casting, drilling and thermal imaging	Chip morphology, tool wear and surface profile	i) increase in spindle speed increases the tool wear and surface profile ii) Abrasion and adhesive wear were observed in the drill tool iii) change from abrasion to adhesive wear is noticed with the increase of the diameter of the drill tool.
2	Liang et al. [15]	Friction induced microstructures	AZ31 magnesium alloy	Morphologies, compositions and hardness of worn surfaces	Pin-on-disc configuration, scanning electron microscope, energy dispersive x-ray spectrometer, hardness tester, dynamic crystallization kinetics	Microstructural evolution, strain hardening, tribological properties, thermal softening, surface oxidation, surface hardening, thermal softening	The transition occurred when the surface layer was softened. Maintenance of mild wear and thermal softening from DRX in subsurface and surface melting were responsible for the severe wear.
3	Wojtowicz et al. [25]	Cutting conditions	Wrought Mg-Zn-Re Alloy	Cutting speed, feed, depth of cut and nose radius	Design of experiment	Turned surfaces, tensile or compressive residual stress, microhardness, twinning and surface roughness	To achieve a given surface integrity and improve fatigue life, optimal cutting conditions could be adopted
4	Varatharajulu et al. [26]	Multicriteria decision making	Mg AZ91	Drilling time, spindle speed, feed rate	TOPSIS – Technique for Order Preference by Similarity to Ideal Solution and COPRAS – Complex Proportional Assessment, Box Behnken design	Optimum combination, identical sequencing, burr height, burr thickness, roughness	i) The trends of various dependent based on heterogeneity of various independent are not identical ii) The optimized results of the desirability function approach are greater in accordance with the TOPSIS and COPRAS top rank.
5	Yazman et al. [9]	Cold chamber die casting parameters	AZ 91 magnesium alloys	Casting temperature, moulding pressure, gate speed	Cold chamber die casting, drilling	Thrust force, tool wear, built-up-edge, built-up layer formation, surface topography, chip morphology and burr formation	i) Higher tensile strengths were obtained for the samples generated from 1000 bar mould than samples from other routes ii) While forming the thrust force, the feed rate showed more effectiveness than the cutting speed. iii) Three types of chips were formed, fan spiral cone and long ribbon type iv) Uniform and transient burrs in different sizes were observed.
6	Umamaheswarrao et al. [10]	Drilling force	AZ91D magnesium alloy	Speed, feed and point angle	Taguchi L16 orthogonal array	Lower drilling force	The drilling force was significantly influenced by point angle, speed and feed.
7	Köklü and Coban [12]	Dipped cryogenic approach	AZ 31 magnesium alloy	Feed rates, cutting speeds, dipped cryogenic application	Cryogenic drilling	Thrust force, temperature, tool wear, chip formation	i) The applied cryogenic drilling method provided less tool wear, smaller chips and reduced amount of adhesions ii) Drilling tests performed in cryogenic environment increase the thrust forces by 32% - 39% compared to dry cutting.
8	Bhowmick and Alpas [19]	Coated drills	Magnesium alloy (AZ 91)	Dry drilling, water lubrication (H ₂ O – MQL)	Drilling	Temperature, cutting torque, drill wear	i) H ₂ O–MQL grew tool life and limited drill torque and temperature. ii) AZ91 workpiece had recrystallization while dry drilling with uncoated HSS and coated NH-DLC drills. iii) No recrystallization found while drilling under H ₂ O–MQL iv) Low coefficient of friction of NH-DLC under H ₂ O–MQL condition limited temperature increase below 55°C, hence drill wear and magnesium adhesion were effectively reduced.
9	De Agustina et al. [20]	Surface quality	Magnesium alloy (AZ91D-F)	Ra, Factorial design 24 feed rate, cutting speed, point angle, cooling system, dry conditions, minimum quality lubrication (MQL) system	Drilling	Improved surface roughness	i) Lower values of Ra than the tool of 118° point angle.
10	Wang et al. [46]	Wear mechanism	Die-cast magnesium alloys	Wear mechanism map	SEM	Adhesive wear, abrasive wear, and diffusion wear	Existence of a minor wear region which is called a safety zone.
11	Sivashankar et al. [13]	Performance characteristics	Mg AZ61 Alloy	Drill diameter, spindle speed, feed rate	Taguchi L9 orthogonal array, Taguchi GRA and GRA analysis, SEM analysis	Optimal parameter	Drill diameter is the significant parameter to minimize the overcut and improve the surface roughness.
12	Bhowmick et al [5]	Quality lubrication	Cast magnesium alloy AM60	MQL – minimum quality lubrication	Drilling, plastic strain and hardness measurement	Temperature, softening	i) MQL drilling provided a stable drilling performance ii) Desirable machining characteristics, smooth hole surface and short chip segments were obtained.

Table 1 A summary of related literature review

The existing research on Taguchi methods for optimisation of electrical discharge machining parameters had been conducted where the AHP-Taguchi, AHP-Taguchi Pareto and AHP-Taguchi-ABC methods had been reported. These methods adopted the traditional factor-level table. One available report on aspect ratios in engineering applications is in the maintenance engineering area [20] and the second one on turning operations [24]. However, no study has been reported on a comprehensive analysis of the aspect ratio characterization and its effect on the optimal parametric settings generated in the drilling engineering domain. Further, no research has presented detailed information on the effect of considering the squares, and cubes of parameters (such as speed and feed rate) and their reciprocals in addition to considering these parameters jointly with them on the optimal parametric setting development. From that viewpoint, however, this research paves the way to examine the influence of using combined direct factors and squares, cubes and their reciprocals in aspect ratios where the direct factors are the spindle speed and feed rate. The combined use of direct factors and aspect ratios is a useful substitution for direct factors alone and it addresses the problem of wrong results from the use of only direct factors. It also tackles the issue of wrong decision-making.

2.3 Problem Definition and Objective

Today, in optimizing the drilling operations' parameters, the factor-level table is the principal element in the determination of the optimal parametric setting using the Taguchi method. However, the prevalent idea is to use the direct factors in this factor-level table, which sometimes leads to wrong results and incorrect decision-making. The problem is serious given the escalating cost of drilling operations regarding the input costs such as material and labour costs. Hence, the need arises to adequately optimize the drilling parameters to shift from local to globally optimal solutions. Correspondingly, drilling research is attracting more scholars globally in search of optimal solutions).

Furthermore, a novel method of modified Taguchi, in which the factor-level framework was developed based on the combination of direct factors and aspect ratios to compute the optimal parametric settings, is proposed. The direct factors are the speed and feed rate while the aspect ratios are the squares of speed, squares of feed rate, a cube of speed, a cube of feed rate, reciprocals of squares of speed, reciprocals of the squares of feed, reciprocals of the cube of speed and reciprocals of the cubes of feed rate. However, for each formulation, the number of factors may be three, consisting of direct factors alone or may be up to five, where direct factors are combined with the aspect ratios.

The data from Varatharajulu et al. [26] was used to validate the proposed method. The data collected by Varatharajulu et al. [26] involves experimentation with the magnesium alloy AZ91 conducted in a drilling process using a three-axis vertical machining centre of the X6323

model and ALTO make. A drill bit of 6mm diameter was used to drill the magnesium material. The description of the drill bit by point angle, flute length, helix angle and overall length are 118° , 57mm, 30° and 93mm, respectively. Samples were produced at three different speeds and three grades of feed rates. Based on the experiential information provided by Varatharajulu et al. [26] about the objective of the present study, the interest of the present authors was shown the two parameters experimented upon by Varatharajulu et al. [26], which are speed and feed rate. From the present authors' perspective, it was thought that the information presented in Table 1 of the report is sufficient enough to actualize the objective of this study and no extensive data setting was pursued.

Furthermore, in this study, the literature data were used to compute the results based on three variants of Taguchi, namely the classical Taguchi method, Taguchi-Pareto method and Taguchi-ABC method. From the previous formulations involving the direct factors and aspect ratios, eight distinct alternatives were formulated. Then each alternative was compared with the next to determine the best alternative based on the results of the highest average signal-to-noise response table. The idea for evaluation is that higher signal-to-noise ratios have a higher quality of performance and are therefore chosen as the better option. Based on this, the best alternative was determined. Afterwards, this best alternative was compared with each of the Taguchi variant methods based on the results of the average signal-to-noise ratios from the response table. Then the overall best formulation was determined from the comparisons and the practical implications arising from the choice in terms of improved surface roughness, which is the outcome of the drilling process, were elaborated. Also discussed is the energy-saving potential of the method. The procedure involved in implementing this research is indicated in Fig. 1.

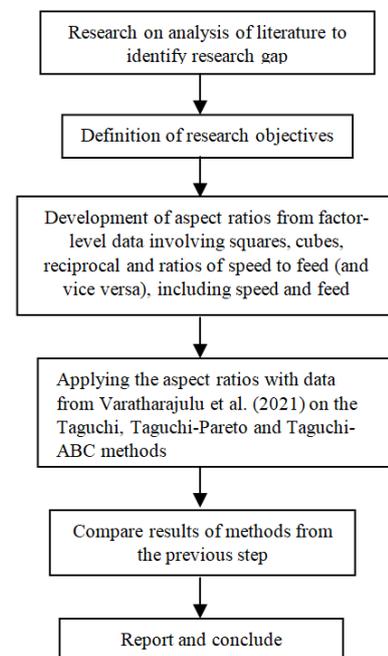


Fig. 1 The procedure for implementing the methods in this article

3. Methods

Magnesium alloys are advanced engineering materials comprising magnesium and other metal elements such as zinc, rare metals, coppers, manganese, zirconium, aluminium and silicon to enhance their physical characteristics such as high strength, outstanding machinability, low specific gravity and low Young's modulus [10], [12], [13], [41]. To understand the landmark achievements in the use of magnesium alloys, it is essential to examine the wide-ranging scope of applications of magnesium alloys in engineering and other aspects of human endeavours generally. First, with a density in the low value of 1.74g/cm^3 , tensile strength in the range between 160 and 365 MPa, an elastic modulus of 45GPa, and Young's modulus of 42GPa, magnesium alloys find their use in automotive industries [2], [4], [10], [12], [13], [20], [30], [32], [33], [41]. Engineers, designers and material scientists servicing the automotive industry have recommended magnesium alloys for transmission. This is on the understanding that the magnesium alloys provide the required physical properties and substandard measures of these properties could lead to transmission failures involving fatalities and huge material losses. The key transmission members of the automobile that relies on magnesium alloys are clutch housing and support brackets in brakes. Second, engineers and designers in aerospace recommend magnesium alloys due to their outstanding physical attributes for several elements in the helicopter. These include the gearbox housings, landing wheels and helicopter rotor fittings. Third, the textile industry is a mechanical intensive industry requiring outstanding physical attributes of the textile machines. Thus, to satisfy this requirement, the use of magnesium alloys has been recommended for the operating pieces of machinery characterized by high-speed activities. Fourth, magnesium alloys have attracted manufacturers of travelling luggage as they are found to demonstrate their outstanding attributes when subjected to such physical attribute demands. A similar case of application involves hand tools used in engineering practices. It also extends ladder manufacture that demands intense physical properties to withstand the physical requirements of its usage. Besides, computer housings are also made of magnesium alloys. Fifth, it is known nowadays that medicine is an important aspect of our lives in the light of the global health crisis of the coronavirus pandemic that affected all nations. Consequently, magnesium alloys find their usage in the manufacture of medical equipment and the creation of wheelchairs as supports for patients; due to the poor health status of patients, lightweight wheelchairs are required for motions at the least energy expenditure. Sixth, today that electronics technology has exploded due to the unprecedented power of computers and the internet's influence; magnesium alloys have a bias in packaging electronics. Similarly, hard drive arms, portable media drives and cellphones are some key components that have a bias for magnesium alloy usage.

3.1 Taguchi Method

The Taguchi method is a bi-attribute method in the context of engineering process selection and optimization [20], [32]. To select parameters among many, the Taguchi method launches its delta values to compare the relative weights of the factor and then decide, based on their magnitudes, what rank are to be allocated to each factor during the drilling process of the magnesium AZ91 alloy. At the same time, the Taguchi method demonstrates its optimization capability by forming an opinion about the optimal parametric setting with which the process variables could be set and compared for improvement and control purposes. Probably, because of this bi-attribute identification with the Taguchi method, it is, preferred to other competing methods used for selection alone, such as the artificial neural network and the factor analysis.

In this work, Table 2 is the foundation table used for the analysis.

S/N	Parameters	Level 1	Level 2	Level 3
1	Spindle speed (revolution per min)	1100	2920	4540
2	Feed rate (mm. per revolution)	0.038	0.076	0.203

Table 2 Parameters and level boundaries by Varatharajulu et al. [26]

Furthermore, the choice of the Taguchi method in the evaluation of process parameters was motivated by the drive to minimize experimental costs. Table 2 contains the actual parameters to be used for the Taguchi optimization process. The orthogonal array for 27 experimental trials is formed in the Minitab 18 edition 2020 for the interpretation of parameters along with their relative columns. After the first experimental trial, the same procedures are repeatedly carried out for additional 26 trials to maximize the response values. The signal-to-noise ratio is well calculated using the Larger the better formula to optimize the parameters on Taguchi [20].

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

Where S/N is the signal-to-noise ratio, n is the number of factors/parameters, $1/y_i^2$ is the relative factors/parameters, \sum is the summation symbol and i is the iteration number.

The signal-to-noise ratio is generated after the optimization process. The response table is then generated after calculating the average of the parameters within the signal-to-noise ratio results. These results are distributed within levels 1 to 3 in between the independent parameters (i.e. spindle speed and feed rate). The first Taguchi optimum parametric settings are calculated by finding the range across their levels in each factor.

3.2 Taguchi-Pareto Method

In the present article, the Taguchi-Pareto method, which is an advancement of the Taguchi method is introduced [20]. The added advantage of the Taguchi-Pareto method over the Taguchi method is that it considered the ordering of the experimental trials and finally ignores the 20% by value, which is considered not important to the objective of the problem being solved as the 80-20 Pareto rule is followed in analysis. The signal-to-noise ratios (SNRs) are first re-arranged from the highest to the lowest. The highest SNR is then computed as the first experimental trial result but with its identity unchanged regarding the numbering of the experimental trial. A cumulative result column is added and the value of the SNR is repeated as the first cumulative result. Then, for the rearranged data set, to obtain the cumulative SNR for the next experimental trial, the first cumulative result is added to the second-highest SNR [20]. A further process is conducted by adding the second cumulative SNR result to the third-highest SNR to obtain the third experimental trial cumulative SNR. The process is accurately followed by the remaining experimental trials until the final result is obtained for the column containing the cumulative experimental trial. This is equal to the total sum of SNR as rearranged from the highest to the lowest. Besides, to transform the obtained values into percentages, an additional column is created where the percentage cumulative/signal-to-noise ratio was computed by dividing each cumulative result of the experimental trial by the SNR total and multiplying the result by 100%. However, according to the Pareto principle, 80%-100% (the last few rows, possibly) are not essential as they do not contribute towards the objective of solving the problem. However, they are characterized by low signal-to-noise ratio results [20].

3.3 Taguchi-ABC Method

The description followed for the implementation of the Taguchi-Pareto method, which terminates at obtaining a % cumulative SNR column, perfectly suits the Taguchi-ABC method also [20]. However, the extension to this method is that the Taguchi-ABC method is segregated into three portions of A, B and C by 80-100%, 70-79% and 1-69%, respectively.

4. Results and discussion

In this article, the Taguchi method, Taguchi-Pareto and Taguchi-ABC methods were deployed to work on the experimental data provided by Varatharajulu et al. [26] to obtain new results for the classical Taguchi method and the new methods of Taguchi-Pareto and Taguchi-ABC. This section reports the results of this technique deployment to solve the drilling problem for the magnesium AZ91 alloy. Furthermore, all the alternatives 1 to 8 for the combined direct and aspect ratios were also analyzed using the three methods of Taguchi, Taguchi-Pareto and Taguchi-ABC and the

details of their results are displayed in this section. However, first, the direct factors are worked on as revealed in the next subsection.

4.1 Direct Factors and Aspect Ratios

In this work, the present author built on the experimental data obtained from the drilling experiments [19] where the speed and feed rate of the machine were established as the relevant parameters to examine the classification schemes of the data according to the TOPSIS and COPRAS methods. In this article, a selection cum optimisation of the drilling process parameters was sought using the Taguchi method. In this method, the ranks produced by the delta values for each parameter yielded the priorities of the parameters. The optimal parametric settings then yielded the best values of the parameters in combination with one another. It is believed that for drilling to Mg AZ91D material, the proportions of one ratio to the other may in addition produce reliable results for judging the performance of the drilling process parameters. These proportional parameters, known as aspect ratios, are introduced in the present work. The principal parameters are S (speed) and F (feed). However, it is understood those certain proportions such as $S^2:1$, $S:F$, $F^2:1$, $1:S^2$, $S:F$ and $1:F^2$ are possible for an examination. Others are $S^3:1$ and $1:F^3$ among others. Thus, in all, nine options are obtained (Table 3).

The evaluation of the new method of Taguchi proceeds with the demonstration of alternative 1, where three factors are formulated, namely S^2 , S/F and F^2 . Notice here that the original factors of speed and feed rate proposed by Varatharajulu et al. [26] were ignored in this alternative as it was not captured during the combinations of parameters, it is however considered in the future when alternatives 5, 6, 7 and 8 are discussed.

Alternative(s)	Factors				
	1	2	3	4	5
1	S^2	S/F	F^2	-	-
2	$1/S^2$	F/S	$1/F^2$	-	-
3	S^3	S/F	F^3	-	-
4	$1/S^3$	F/S	$1/F^3$	-	-
5	S	F	S^2	S/F	F^2
6	S	F	$1/S^2$	F/S	$1/F^2$
7	S	F	S^3	S/F	F^3
8	S	F	$1/S^3$	F/S	$1/F^3$

Key: S – Speed (revolution per minutes)-(rev/m), F – Feed Rate (mm. per revolution)-(mm/rev), S^2 – Square of Speed (revolution per minutes-square)-(rev/m)², S^3 – Cube of Speed (revolution per minutes-cube)-(rev/m)³, F^2 – Square of Feed Rate (mm. per revolution-square)-(mm/rev)², F^3 – Cube of Feed Rate (mm. per revolution-cube)-(mm/rev)³

Table 3 Taguchi alternatives for parameters of the drilling optimization process

For alternative 1, the factor-level table is set up for further optimisation steps, Table 2. In this table, the

second column consisting of the factor S^2 is computed by referring to the factor level table by Varatharajulu et al. [26]. In this instance, 1100rpm was indicated as the speed, S , for level 1. But by squaring S , a value of 1210,000 (rpm) is obtained. Next in the third column, the proportion of S/F is computed by extracting the values of 1100rpm and 0.038mm/rev for speed and feed rate respectively, from the factor-level table of Varatharajulu et al. [26] to yield 28947.368rpm (rev/mm). Furthermore, the last column is obtained by squaring the feed rate obtained from Varatharajulu et al. [26]. This yields $0.001444 \text{ (mm/rev)}^2$. The next step is to develop the signal-to-noise ratio table (Table 4), which consists of the orthogonal arrays for the factors and the application of one, or three criteria of the signal-to-noise ratios named as the smaller-the-better criterion, nominal the best criterion and larger the best criterion. In this case, the smaller the better criterion is used such as the lower values of speed and feed rate are desired to attain the goal of defect-free and quality drilling operations. To commend the signal-to-noise ratio computation, the L_9 orthogonal arrays, indicating 1, 2 and 3 for levels 1, 2 and 3 are shown in columns 3 to 5. Columns 6 to 8 are the translated orthogonal array entries to actual values as interpreted from the factor-level table.

4.2 Findings

In Table 3, five major factors are formed as the maximum while the three factors are formed as the minimum. The three factors are often the square or cube of speed and/or feed rate. Also, the reciprocals of these squares and cubes are considered amongst the three factors in any alternatives with three factors. For instance, Alternative 1 contains the squares of the spindle speed, feed rate and the ratio of the spindle speed to the feed rate as the only three factors. Thus, three factors are maintained from Alternatives 1 to 4. In situations where five factors are used such as in Alternatives 5 to 8, the two extra factors of spindle speed

and feed rate are used. An example is Alternative 5 which contains the spindle speed, feed rate, the square of the spindle speed, the ratio of the spindle speed to feed rate and the square of the feed rate. A similar formulation may be observed in Alternatives 6 to 8. The commencement of this analysis is with Alternative 1 where the optimal parametric setting is pursued. To achieve this, the factor level table is shown in Table 4.

Level	Factors		
	S^2	S/F	F^2
1	1210000	28947.37	0.001
2	8526400	38421.05	0.006
3	20611600	22364.53	0.041

Table 4 Alternative 1 with levels versus factors 1, 2 and 3

The purpose of Table 4 is to provide a basis for relating the factors assumed to be the most important to the drilling process for the Magnesium AZ91 alloy to the levels defined for the problem. Based on the previously defined factor-level table by Varatharajulu et al. [26], three factors are now formed from the two factors defined by the authors. These factors are S^2 , S/F , and F^2 . This implies that the values of the spindle speed which were given for level 1 by that Varatharajulu et al. [26], as 1100rpm is squared as $1210000 \text{ (rev/min)}^2$. This becomes the first factor for level 1. Still, on Level 1, the second factor is S/F , as S was given as 1100rpm and F was given as 0.038mm/rev, the factor S/F assumes a value of 28947.36842 (rev²/mm-min) for level 1. Besides, the third factor for level 1 is obtained from 0.038(mm/rev) in its squared from $0.001444 \text{ (mm/rev)}^2$. Furthermore, the values of S^2 , S/F and F^2 are obtained for levels 2 and 3 as shown in Table 5.

Experimental trials	S^2	S/F	F^2	S^2	S/F	F^2	SNR
1	1	1	1	1210000	28947.37	0.001	-20.62
2	1	2	2	1210000	38421.05	0.006	-14.60
3	1	3	3	1210000	22364.53	0.041	-6.07
4	2	1	2	8526400	28947.37	0.006	-14.60
5	2	2	3	8526400	38421.05	0.041	-6.07
6	2	3	1	8526400	22364.53	0.001	-20.62
7	3	1	3	20611600	28947.37	0.041	-6.07
8	3	2	1	20611600	38421.05	0.001	-20.62
9	3	3	2	20611600	22364.53	0.006	-14.60

Table 5 Alternative 1 – Factors, orthogonal arrays, their translated values and signal-to-noise ratios

Moreover, Table 5 shows the factors which are principally S^2 , S/F and F^2 . It also reveals the orthogonal arrays, which is the L_9 type obtained from the Minitab 18 (2020) software. The number of factors is three and the number of levels is three which gives the specification by the Minitab software version 18(2000) as Taguchi array of L_9 (3 by 3). Thus in Table 5, the first column contains the nine experimental trials while the second, third and fourth columns contain the orthogonal arrays. Besides, the transformed arrays are contained in the fifth, sixth and seventh columns. The eighth column contains the signal-to-noise ratio values. This was computed using the Larger the better signal-noise ratio criterion which

has been discussed in the session on methods. To calculate this value, the squares of $1210000 \text{ (rev/min)}^2$, $28947.3684 \text{ (rev}^2\text{/mm-min)}$ and $0.0014 \text{ (mm/rev)}^2$ are first computed. Then each of these squared values is converted to reciprocals while the results are summed up. Then the average of these three values is obtained. Furthermore, the logarithm of the average is calculated while the outcome is multiplied by -10 to obtain the final value of -20.6228 for experimental trial 1. For experimental trials 2 up to 9, the same procedure is followed while the values of -14.6022 (experimental trial 2) up to -14.6022 (experimental trial 9) are obtained.

	Alternative 1			Alternative 2			Alternative 3			Alternative 4		
	Factors			Factors			Factors			Factors		
Level	S^2	S/F	F^2	$1/S^2$	F/S	$1/F^2$	S^3	S/F	F^3	$1/S^3$	F/S	$1/F^3$
1	-13.76	-13.76	-20.62	-116.89	-130.75	-130.75	-59.87	-59.87	-80.44	-177.71	-198.51	-198.51
2	-13.76	-13.76	-14.60	-133.84	-130.75	-130.75	-59.87	-59.87	-62.38	-203.15	-198.51	-198.51
3	-13.76	-13.76	-6.07	-141.51	-130.75	-130.75	-59.87	-59.87	-36.78	-214.65	-198.51	-198.51
Delta	1.02E-06	1.31E-06	14.55	24.62	0.0010	0.0010	1.35E-13	1.35E-13	43.66	36.94	7.99E-10	7.96E-10
Ranking	3 rd	2 nd	1 st	1 st	2 nd	3 rd	2 nd	2 nd	1 st	1 st	2 nd	3 rd

Table 6 Response table (averages of signal-to-noise ratios) – Alternatives 1 to 4

Besides, the signal-to-noise ratio is further summarized into averages known as averages of signal-to-noise ratios (Table 6). It is also called the response table. Table 6 has columns for factors which include S^2 , S/F , and F^2 as well as columns for levels which include levels 1 to 3. To explain how the table is calculated, consider level 1 which is the second row of the table. Under this row, there are three factors S^2 , S/F , and F^2 . To obtain the values at the intersection of S^2 and level 1, the authors referred to Table 5. Here of interest to the researcher is the second column is for factor S^2 . Under this column, level 1 which is indicated as "1" appears under experimental trials 1, 2 and 3. The corresponding values at these three locations of signal-to-noise ratio are -20.62, -14.60 and -6.07. By finding the average of these as -13.76, it is indicated in Table 6. This approach is used to compute all the other entries in Table 5. The delta values for each factor are then obtained as the difference between the largest average signal-to-noise ratio (i.e. -13.76) and the lowest (i.e. -20.62), which gives the 1.02×10^{-6} . This approach is used to compute the other delta values of the factors S/F and F^2 . Next, the ranks are obtained based on the arrangement of the highest to the lowest delta values. In this situation, the factor F^2 attains the first rank, S/F attains the second rank and S^2 attained the third rank. Besides these calculations, an interesting conclusion relates to the optimal parametric settings for the process. In this instance, for each factor, the highest average signal-to-noise ratio is located and forms part of the whole expression for the optimal parametric settings. For the particular case considered, the highest value of the average signal-to-

noise ratio is obtained at level 2 for factor S^2 . For factor S/F , it is also at level 2 while for factor F^2 , it is obtained at level 3. This means that the optimal parametric setting is $(S^2)_2(S/F)_2(F^2)_3$. The interpretation is that the optimal parametric setting is $8526400 \text{ (rev/min)}^2$, $38421.0526 \text{ (rev}^2\text{/mm-min)}$ and $0.0412 \text{ (mm/rev)}^2$.

To further the work, the procedure used in establishing the factors and levels from an interpretation of Varatharajulu et al. [26] data factors and levels are followed. Note also, the procedures for obtaining the translated orthogonal arrays, signal-to-noise ratio and response tables. All these procedures were applied to the other alternatives namely Alternative 2 to Alternative 8 and the summarized results are shown in the response table for all these alternatives (Table 6 to 9). In Table 6, the optimal parametric setting of alternative 2 may be read as $(1/S^2)_1 (F/S)_3 (1/F)_3$, which is interpreted as $8.26446 \times 10^{-7} \text{ (min/rev)}^2$ and $4.47137 \times 10^{-5} \text{ (mm-m/rev}^2)$ and $24.26654 \text{ (rev/mm)}^2$.

In comparison with the results from Alternative 1, the averages of the signal-to-noise ratios obtained in Table 6 (Alternative 2) are lower compared to the averages of the signal-to-noise ratios in Table 6 (Alternative 1). This suggests that it is possible to obtain a more difficult drilling process by adopting the optimal parametric settings of Alternative 2 instead of Alternative 1. This is because usually, a higher signal to noise is favourable to use in the drilling process as it is known in the literature that it gives an improved performance during process activities. The implication is less judicious utilization of energy as energy usage is

more and energy is wasted in the overall process. Besides, the labour cost increases as more labour hours are invested than anticipated. Furthermore, higher surface roughness exists such that the output of the machined magnesium AZ91 alloys material fails to meet the expected standard if Alternative 2 is used on the CNC drilling machine. In essence, Alternative 1 is preferred over Alternative 2. In Alternative 3, the optimal parametric setting is obtained as $(S^3)_1(S/F)_1(F^3)_3$, $(S^3)_2(S/F)_2(F^3)_3$ and $(S^3)_3(S/F)_3(F^3)_3$.

Matched against Alternative 1, it is observed that the averages of signal-to-noise ratios obtained in Table 6 (Alternative 3) are higher than that of the averages obtained in Table 5 (Alternative 2) but lower when compared to Table 6 (Alternative 1). Therefore, by implementing the optimal parametric settings of Alternative 3, the performance of the machining process exceeds the projected performance of Alternative 1. In essence, from Alternatives 1, 2 and 3, Alternative 1 is the best. This reflects a lower energy usage and possible improved surface roughness values than alternatives 2 and 3. Alternative 2 is better than Alternative 4 since its

averages of the signal-to-noise ratios are higher than the values of that of Alternative 4. To further the analysis, it was discovered that the averages of signal-to-noise ratios, Table 6 (Alternative 4), are lower than that of Alternatives 1, 2, and 3.

The optimal parametric setting is $(1/S^3)_1 (F/S)_1 (1/F^3)_1$, $(1/S^3)_1 (F/S)_2 (1/F^3)_2$, $(1/S^3)_1 (F/S)_3 (1/F^3)_3$, which was interpreted as $7.51315 \times 10^{10}(\text{m/rev})^3$, $3.45455 \times 10^5(\text{mm-m/rev}^2)$, $18224.23(\text{rev/mm})^3$, $7.51315 \times 10^{10}(\text{m/rev})^3$, $2.60274 \times 10^5(\text{mm-m/rev}^2)$, $2278.029(\text{rev/mm})^3$, $7.51315 \times 10^{10}(\text{m/rev})^3$, $4.47137 \times 10^5(\text{mm-m/rev}^2)$ and $119.5396(\text{rev/mm})^3$. This suggests the possibility of machining inadequacies on the material as a result of unstable cutting tool geometry and tool wear leading to inaccurate material finish [46]. The higher the machine inaccuracy the higher the chip breaking properties. The surface roughness will be more significant. Moreover, in comparison of Table 7 (Alternative 5) averages of signal-to-noise ratio to that of Table 6 (Alternative 4) and Table 6 (Alternative 3), the data were higher as compared to the latter.

Level	Alternative 5					Alternative 6				
	S	F	S ²	S/F	F ²	S	F	1/S ²	F/S	1/F ²
1	-36.64	-37.26	-36.64	-36.637	-49.82	-128.50	-128.50	-114.67	-128.53	-128.53
2	-36.64	-36.48	-36.64	-36.637	-37.82	-128.50	-128.50	-131.63	-128.53	-128.53
3	-36.64	-36.16	-36.64	-36.637	-22.27	-128.50	-128.50	-139.29	-128.53	-128.53
Delta	1E-09	1.101	3E-10	3E-10	27.554	1E-03	0.001	24.6238	0.000987	0
Ranking	3 rd	2 nd	4 th	5 th	1 st	3 rd	4 th	1 st	2 nd	5 th

Table 7 Signal to noise ratio responses - Alternatives 5 and 6

The optimal parametric setting is obtained as $S_1 F_3 (S^2)_1 (S/F)_1 (F^2)_3$, $S_2 F_3 (S^2)_2 (S/F)_2 (F^2)_3$ and $S_3 F_3 (S^2)_3 (S/F)_3 (F^2)_3$ which was interpreted as 1100(rev/min), 0.203(mm/rev), 1210000(rev/m)², 28947.37(rev²/mm-m), 0.041209(mm/rev)², 2920(rev/min), 0.203(mm/rev), 1210000(rev/m)², 38421.05(rev²/mm-m), 0.041209(mm/rev)², 4540(rev/min), 0.203(mm/rev), 2.1 x 10⁷(rev/m)², 22364.53(rev²/mm-m), 0.041209(mm/rev)². This suggests that the rate of feed is higher than the spindle speed of the cutting tool leading to effective drilling of the hole within the material. Thus the feed rate increment minimizes the surface roughness and maximizes the fine grain size of the microspheres. Consequently, the level of value divergence between the averages of the signal-to-noise ratio of Alternative 1 and Alternative 5 varied significantly. There is an indication that the qualities numbers of input parameters influenced of output parameters obtained. Next, the averages of signal-to-noise ratios of Table 7 (Alternative 6) were considered in this work. In comparison, the averages of signal-to-noise ratios obtained were thrice lowered than the values obtained in Table 7 (Alternative 5).

The optimal parametric setting is obtained as, $S_3 F_2 (1/S^2)_1 (F/S)_3 (1/F^2)_1$, $S_3 F_2 (1/S^2)_1 (F/S)_3 (1/F^2)_2$ and $S_3 F_2 (1/S^2)_1 (F/S)_3 (1/F^2)_3$ which is interpreted as 4540

(rev/min), 0.076(mm/rev), $8.26 \times 10^7(\text{m/rev})^2$, $4.47 \times 10^5(\text{mm-m/rev}^2)$, 692.5208 (rev/mm)², 4540 (rev/min), 0.076(mm/rev), $8.26 \times 10^7(\text{m/rev})^2$, $4.47 \times 10^5(\text{mm-m/rev}^2)$, 173.1302 (rev/mm)² and 4540 (rev/min), 0.076(mm/rev), $8.26 \times 10^7(\text{m/rev})^2$, $4.47 \times 10^5(\text{mm-m/rev}^2)$, 24.26654(rev/mm)². The result in this trial indicates insignificant changes in averages of signal-to-noise ratio for speed, feed rate and the ratio of feed rate to speed within levels 1 to 3. However, the reciprocals of feed rate square were recorded constant whilst the reciprocals of spindle speed square varied within the three levels considerably. It could be suggested that the spindle speed contribution to effective machinability of magnesium AZ91 at a constant feed rate would influence the output product of the material with normal energy machining operation. Also, the result obtained from Table 8 (Alternative 7) averages of signal to noise ratio shows the optimum parametric settings as $S_1 F_3 (S^3)_1 (S/F)_1 (F^3)_3$, $S_2 F_3 (S^3)_2 (S/F)_2 (F^3)_3$ and $S_3 F_3 (S^3)_3 (S/F)_3 (F^3)_3$ interpreted as 1100(rev/min), 0.203(mm/rev), $1 \times 10^9(\text{rev/m})^3$, 28947(rev²/mm-m), 0.0084(mm/rev)³, 2920(rev/min), 0.203(mm/rev), $2 \times 10^{10}(\text{rev/m})^3$, 38421(rev²/mm-m), 0.0084(mm/rev)³ and 4540(rev/min), 0.203(mm/rev), $9 \times 10^{10}(\text{rev/m})^3$, 22365(rev²/mm-m), 0.0084(mm/rev)³.

Level	Alternative 7					Alternative 8				
	S	F	S ³	S/F	F ³	S	F	1/S ³	F/S	1/F ³
1	-57.68	-57.72	-57.68	-57.68	-78.22	-82.32	-82.32	-82.32	-82.24	-82.32
2	-57.68	-57.67	-57.68	-57.68	-60.16	-82.32	-82.32	-82.32	-84.70	-82.32
3	-57.68	-57.65	-57.68	-57.68	-34.65	-82.32	-82.32	-82.32	-80.00	-82.32
Delta	8E-11	0.0662	1.14E-12	1.17E-12	43.5744	1.11E-06	3.74E-06	1.17E-06	4.7002	3.84E-13
Ranking	3 rd	2 nd	5 th	4 th	1 st	4 th	2 nd	3 rd	1 st	5 th

Table 8 Signal to noise ratio responses – Alternatives 7 and 8

However, the average of signal to noise ratio is lower than the result obtained in Alternative 3, thereby reflecting average energy usage and minimum surface roughness of the material after the finish. It is suggested that the impressive values of feed rate affected the machining process more than the spindle speed thereby creating low usage of energy and obtaining a normal surface finish. The rate of feed and quality of the material under consideration would also affect the chip structure and perfect roundness of drilled hole.

Therefore, to further the analysis, Table 8 (Alternative 8) SNR optimal parametric setting is $S_1F_3(1/S^3)_1(F/S)_1(1/F^3)_3$, $S_2F_3(1/S^3)_2(F/S)_2(1/F^3)_3$ and $S_3F_3(1/S^3)_3(F/S)_3(1/F^3)_3$ imply 1100 rev/min, 0.203 mm/rev, 18224.23 (m/rev)³, 3.45455E-05 mm-m/rev², 119.5396 (rev/mm)³, 2920 rev/min, 0.203(mm/rev), 2278.029 (m/rev)³, 2.60274E-05 mm-m/rev², 119.5396 (rev/mm)³, 4540 rev/min, 0.203 mm/rev, 119.5396 (m/rev)³, 4.47137E-05 mm-m/rev², 119.5396 (rev/mm)³.

This result shows lower averages of SNR as compared to Alternative 7. The average data obtained are nearly similar for all the parameters (speed, feed rate, reciprocals of speed and feed rate) considered although they varied. The range between the values obtained is negligibly matching the fraction of two major factors, speed and feed rate against other independent factors. Furthermore, Alternative 8 revealed a below-expected performance of the machining process as compared to Alternative 1 having the best data in the previous experimental trials. However, there is a tendency for a stable machining process if the rate of feed and speed does not exceed the set values as proposed by the response table. Consequently, matching all the eight alternatives against one another, it could be suggested that Alternative 1 optimal parametric setting would provide a good surface finish, surface roughness reduction, chip morphology, thermal energy and cutting tool geometry during the machining of magnesium AZ91.

In summary, by observing the results from all the eight Alternatives (1 to 8) considered in this work, the following observations are made:

- 1) It was discovered that the factors F², S/F and S² attained first, second and third delta rankings respectively. Also, the highest signal-to-noise ratios averages determine the optimal

parametric settings for each alternative in the process.

- 2) Also, the Alternative 2 data values are lower in averages of signal-to-noise ratio, suggesting a more difficult drilling process and more energy usage.
- 3) More so, Alternative 3 has a higher average signal-to-noise ratio than Alternative 2 which made the performance of the machining process exceed the projected performance of Alternative 1.
- 4) Due to much lower signal-to-noise ratio averages, the tendency of machining inadequacies on the experimented material is unavoidable as this may lead to an imperfect surface finish.
- 5) Additionally, the feed rate is more significant than the other factors considered, as there are possibilities of effective drilling and reduced surface roughness.
- 6) It was also observed that the spindle speed contributed to influencing the optimum performance of feed into the material during machining.
- 7) Moreover, there is low usage of energy and normal surface finish due to the effective rate of feed.
- 8) There is a tendency for a stable machining process if the rate of feed and speed does not exceed the set values proposed by the response table.

However, to progress, there is a need to compare the best result with the outcome obtained from the Taguchi method, Taguchi ABC and Taguchi Pareto method using the original data. To achieve this aim, the results of the above-mentioned methods are presented. Furthermore, the Taguchi results are expressed in Table 8 as the response table alone since the rudiments of computing the Taguchi method using the data by Varatharajulu et al. [26] are the same as those implemented for (Alternative 1 to 8) of this work. Thus, the response table, Table 9 is shown as follows:

Level	Taguchi method		Taguchi Pareto method		Taguchi ABC method (Part A)		Taguchi ABC method (Part B)		Taguchi ABC method (Part C)	
	Factors		Factors		Factors		Factors		Factors	
Level	S	F	S	F	S	F	S	F	S	F
1	-18.54	-25.39	-15.11	-25.39	-169.63	-25.39	0	-25.39	-25.39	-25.39
2	-18.54	-19.37	-16.58	-194.43	-15.11	-19.37	-25.39	0	-25.39	0
3	-18.54	-10.84	-18.54	-54.20	-17.68	-10.84	-25.39	0	0	0
Delta	5.45E-08	14.55	3.43	169.03	154.53	14.55	25.39	25.39	25.39	25.39
Ranking	2 nd	1 st	2 nd	1 st	1 st	2 nd	1 st	1 st	1 st	1 st

Table 9 Signal to noise ratio responses – Taguchi method, Taguchi Pareto and Taguchi ABC method (Parts A, B and C)

The interpretation of this table is that the signal-to-noise ratio is compressed into averages of signal-to-noise ratios. It is also called the signal-to-noise ratio response table. Table 8 (Alternative 8) has columns for factors which include S, F, 1/S³, F/S and 1/F³ as well as columns for levels which includes level 1-3. The table is calculated by considering level 1 which is the second row of the table. Within this row, there are five factors S, F, 1/S³, F/S and 1/F³. The value at the intersection of S and level 1 is obtained. The same process is repeated for F, 1/S³, F/S and 1/F³ to obtain their respective values at level 1. This procedure is followed to obtain values for all the remaining factors corresponding to level 2 and later level 3 in Table 8. The crucial corresponding values of F/S within three levels of signal-to-noise ratio are -82.24, -84.70 and -80.00. The delta values for each factor are then obtained as the difference between the largest average signal-to-noise ratio (i.e. -80.00) and the lowest (i.e. -84.70) and resulting in 4.70. This approach is used to compute the other delta values of the factors S, F, 1/S³ and 1/F³. In addition, the ranks are obtained by arranging from the highest to the lowest delta values. It was calculated that the factor F/S became the first rank, F was ranked second and 1/S³ attained the third rank, S became the fourth rank and 1/F³ was ranked fifth. The optimal parametric setting which narrates the best value for the machining process is extracted as the highest value of the signal-to-noise ratio from each factor considered. Table 8 (Alternative 8) SNR optimal parametric setting is S₁F₃(1/S³)₁(F/S)₁(1/F³)₃, the highest value of the average signal to noise ratio is obtained at level 1 for factor S, the highest value of the average

signal to noise ratio is obtained at level 3 for factor F, the highest value of the average signal to noise ratio is obtained at level 1 for factor 1/S³, the highest value of the average signal to noise ratio is obtained at level 1 for factor F/S, the highest value of the average signal to noise ratio is obtained at level 3 for factor 1/F³. This follows the same interpretation for the following optimal parametric settings which include S₂F₃(1/S³)₂(F/S)₂(1/F³)₃ and S₃F₃(1/S³)₃(F/S)₃(1/F³)₃. Below is Table 8 (Alternative 8) SNR optimal parametric setting: S₁F₃(1/S³)₁(F/S)₁(1/F³)₃, S₂F₃(1/S³)₂(F/S)₂(1/F³)₃ and S₃F₃(1/S³)₃(F/S)₃(1/F³)₃ which is interpreted further as; 1100 rev/min, 0.203 mm/rev, 18224.23 (m/rev)³, 3.45455E-05 mm-m/rev², 119.5396 (rev/mm)³, 2920 rev/min, 0.203(mm/rev), 2278.029 (m/rev)³, 2.60274E-05 mm-m/rev², 119.5396 (rev/mm)³, 4540 rev/min, 0.203 mm/rev, 119.5396 (m/rev)³, 4.47137E-05 mm-m/rev², 119.5396 (rev/mm)³.

Then in comparison with Alternative 1, which is the best option so far considered, the Taguchi method performs lower than it. Thus, we are furthering the analysis with the Taguchi method or Alternative 1 as the best option. Next, the Taguchi Pareto method is considered. While details of the Taguchi Pareto method are available in the literature which can be referred to for a deeper understanding of its implementation procedure only the response table is shown to represent the method. From the results, (Table 10), Alternative 1 is still better than Taguchi Pareto which is therefore carried forward as the best method.

Description	Method 1 (Taguchi Method)	Method 2 (Alternative 1)	Method 3 (Taguchi Pareto)	Method 4 (Taguchi ABC)
Optimal parametric setting (OPS)	S ₃ F ₃ where S ₃ is read from the average signal-to-noise ratio table as -18.5357 and F ₃ is -10.8398	(S ²) ₂ (S/F) ₂ (F ²) ₂ where (S ²) ₂ is read from the average signal to noise ratio table as -13.7645, (S/F) ₂ is -13.7645 and (F ²) ₂ is -6.0657	S ₁ F ₁ where S ₁ is read from the average signal-to-noise ratio table as -15.1066 and F ₁ is -25.394	For Part A, the OPS is S ₂ F ₃ where S ₂ is read from the average signal-to-noise ratio table as -15.1066 and F ₃ is -10.8398. For Part B, the OPSs are in two versions. The first is S ₁ F ₂ where S ₁ is read from the average signal-to-noise ratio as 0 and F ₂ is 0. For the second version, S ₁ F ₃ S ₁ is read from the average signal-to-noise ratio as 0 and F ₃ is 0. For Part C, the OPSs are also in two versions. The first is S ₃ F ₂ where S ₃ is read from the average signal-to-noise ratio as 0 and F ₂ is 0. For the second version, S ₃ F ₃ S ₃ is read from the average signal-to-noise ratio as 0 and F ₃ is 0.

Table 10 Comparison of optimal parametric settings for all methods

Before the final comparison, all the three options of the Taguchi ABC that is Taguchi ABC with emphasis on part A, Taguchi ABC with emphasis on part B and Taguchi ABC with emphasis on part C. In these three comparisons, Taguchi ABC with emphasis on part B ties up with Taguchi ABC with emphasis on part C. This is because they exhibit the average signal-to-noise ratio of zero as opposed to the values lower than zero for the Taguchi ABC with emphasis on part A. To progress with the final comparison, these two aspects are compared with the results of Alternative 1. Surprisingly, they exceed the performance of Alternative 1. Thus, the overall conclusion is that the Taguchi ABC with emphasis on part B as well as Taguchi ABC with emphasis on part C is the best from the analysis. They are therefore recommended to the process manager to set the machines with such performance characteristics. The outcome of processing the magnesium AZ91 alloy will be compared each time with that of these two methods which are judged the best.

Having presented the results of the findings, one may ask what the new thing/knowledge that the present research has found. It is worth knowing that with an extensive research effort, researchers were able to successfully identify the significance of using the aspect ratios in practice [20], which yielded a departure from the literature regarding performance evaluation for a container seaport facility. However, there is a need to better understand how the aspect ratios are characterized and classified within the context of a drilling environment. More importantly, the characterization and classification of the aspect ratios to involve squares and cubes as well as their reciprocals is a key pursuit of the present study. This goal is achieved by closely observing the methodology and procedures suggested by Oke and Adekoya [23] and then developing a new set of rules useful in employing the aspect ratios for the drilling operation of the AZ91 magnesium alloy. Thus, apart from the new rules proposed, a case investigation to support and validate the new rules is explored for the drilling situation.

5. Conclusions

In the article, the optimization of drilling parameters of Magnesium AZ 91 alloy using the unique aspect ratio-based Taguchi method. In this situation, as opposed to the current state of knowledge in the literature, squares and cubes of aspect ratios are formulated and combined with the direct factors to make up the maximum of five factors while the minimum number of factors is three. Arising from these, eight different formulations known as alternatives were made and tested with the data Varatharajulu et al. [26], which depends on the experimental data carried out in the laboratory. Furthermore, to validate the results of this work, three variants of the Taguchi method were evaluated and compared with the best alternatives from the eight groups of alternatives. These variants are the Taguchi

method, Taguchi Pareto method and Taguchi ABC method. From the results of the analysis carried out in this work the following conclusions are made:

- 1) In this article, the twelve surveyed parameters are S, F, S/F, F/S, S^2 , $1/S^2$, F^2 , $1/F^2$, S^3 , $1/S^3$, F^3 and $1/F^3$. Out of these, the parameters attaining the first position in ranking in the results given by the response tables for all the alternatives 1 to 8 were noted. They are judged as having the greatest influence on the surface roughness outcome while other parameters attaining the second to the last ranking were judged to have no significant influence on surface roughness. Meanwhile, the parameters F^2 , F^3 , $1/S^2$, $1/S^3$ and F/S attained the first position in the various alternatives and have a significant influence on the surface roughness outcome of AZ91 magnesium alloy during the drilling process. However, parameters including S, F, S/F, S^2 , $1/F^2$, S^3 and $1/F^3$ have no significant influence on the surface roughness outcome in the drilling of AZ91 magnesium alloy.
- 2) This is the first time that the selection and optimisation of the parametric setting for drilling (speed, feed rate, square and cube of square and feed) will be used for the drilling process by deploying the Taguchi, Taguchi-Pareto and Taguchi-ABC methods.
- 3) Considering the first position only in all the alternatives, the ranking order of parameters coincides with 25% for F^2 , 25% for F^3 , 25% for $1/S^2$, 12.5% for $1/S^3$ and 2.5% for F/S. Stated differently, in all the eight alternatives considered in this article, F^2 was 1st in 25% of the cases, F^3 came first in 25% of the situations, $1/S^2$ was positioned 1st in 25% of the alternatives, $1/S^3$ was placed 1st in 12.5% of the cases and F/S was placed 1st in the 12.5% of the cases. However, factors S, F, S/F, S^2 , $1/F^2$, S^3 and $1/F^3$ took other positions apart from 1st in each alternative.
- 4) To ascertain minimum roughness, the optimal values while combining F^2 , F^3 , $1/S^2$, $1/S^3$ and F/S may be pursued using the signal-to-noise determination route to the optimal parametric setting specification.
- 5) Among all the alternatives, numbering 1 to 8, the best alternative is alternative 1. The decision was made on the best alternative based on the values of the average signal-to-noise ratio in the response table. It is known that higher signal-to-noise ratios are desired from the drilling process and therefore used as a criterion for evaluation and judgment of the best alternatives.
- 6) In a comparison of the alternatives with the three variants of Taguchi methods, the Taguchi ABC methods merged as the best overall method. This is based on the results displayed by the Taguchi ABC with part B and Taguchi ABC with part C.

- 7) Based on the results, the method of Taguchi ABC with parts B and C, which exhibit higher signal-to-noise ratios, would have reduced surface roughness. Furthermore, the energy utilization using the method in setting up the drilling process would be less than the other methods and therefore recommended for use regarding energy conservation in the drilling operation.
- 8) It is known from the literature that a higher feed rate within certain limits promotes the continuous formulation of chips during the drilling operation. However, based on the signal-to-noise ratios (average), it was known from the Taguchi method that the feed rate exceeds the spindle speed in signal-to-noise ratio strength. Therefore, there is a higher tendency of generating continuous but controlled chips during the drilling process. This is declared from the results of the Taguchi method.

A principal knowledge gained in this study is that these varied aspect ratios in the square of the feed, the ratio of the speed to feed and the square of the speed substantially affect the surface finish of the processed AZ91 magnesium alloy during the drilling process. From the execution of this work, new and promising studies in the future are expected. Therefore, in the future, it is necessary to conduct studies that incorporate economic aspects as useful information to guarantee the sustainability of the drilling process. Furthermore, a concept such as the inflationary rate and interest factor could be introduced into the work to make the work economically robust. In this work, the novel elements are as follows:

- 1) The introduction of combined direct factor and aspect ratios which considered squares, cubes and their reciprocals to optimize the drilling process parameters whilst conserving energy is made. This is the first time that such a combination of factors would be made to solve the problem of drilling cost-effectively using Magnesium AZ91 alloy.
- 2) The work compares a wide range of alternative methods comprising direct and aspect ratios with three variants of the Taguchi method. These variants are the Taguchi method, the Taguchi Pareto and the Taguchi ABC methods.

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