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Parametric Selection and Optimization of Al-Mg-Mn-Zr-Er Alloy Weld Bead Geometry Welded by Laser Using the Aspect Ratio-Based Taguchi Method

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A B S T R A C T

At present, there is a continuous escalation of labour costs, material costs and other welding-related costs and stabilizing them is challenging. Therefore, optimization of the welding process is essential to stabilize the situation. In this article, an aspect ratio-based Taguchi method is proposed to control the operational performance of the laser welding process while welding the Al-Mg-Mn-Zr-Er alloy sheets. The direct parameters considered are the laser power (LP), welding speed (WS) and welding feed rate (WFR). The aspect ratios analyzed are LP/WS, LP/WFR, WS/LP, WS/WFR, WFR/LP and WFR/WS. The aspect ratios are introduced into the factor/level framework, and the results, transmitted as orthogonal arrays are changed to signal-to-noise ratios. The final results are the delta values, ranks and optimal parametric settings. The principal results indicate that for the LPWS and LP/WFR formulation, the optimal parametric setting is $LP/WS_1LP/WFR_3$, which is interpreted as 1.6 kWmin/m LP/WS and 0.35 kWmin/m of LP/WFR. The corresponding delta values are 3.875 and 2.6288 while the positions of 1st and 2nd were obtained by LP/WS and LP/WFR aspect ratios, respectively. It was established that the LP/WS, WS/WFR and WFR/LP are the most important aspect ratios for the laser welding of Al-Mg-Mn-Zr-Er alloy sheets. Therefore, prioritization in resource distribution should be given to these parameters according to their positions. This article serves as a source of information for welding decision-making.

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1. INTRODUCTION

In laser welding, the phenomenon of temperature distribution is a single important element, which occurs in the weld beads (Yang et al., 2018). This phenomenon makes it necessary and urgent to study how the parameters of the welding process could be optimized (Yang et al., 2012a; Lei et al., 2019). In multipass welding, the degree of control of temperature distribution strongly influences the mechanical properties, material microstructure, residual stress and hardness of the welded material upon being cooled to room temperature. However, it is known that the majority of the heat is concentrated at the weld beads therefore triggering intense attention to this material part as an exceptional aspect to focus on during a successful temperature control endeavor (Dong et al., 2021). Moreover, the temperature distribution in the weld bead should be optimized to achieve the utmost quality of the laser-welded material. Therefore, some forms of methods of optimization are essential to achieve the set goals of the welding process (Yang et al., 2018).

In this context, the process parameters of laser welding should be established and monitored for the optimum achievement of the process goals. Interestingly several optimization methods have been successfully applied in engineering literature. This includes traditional and non-traditional methods. The available methods include linear and non-linear programming, geometric and convex programming, branch and bound, genetic algorithms, differential evolution and Taguchi methods, among others. However, two very important criteria in the choice of the method to use in solving the optimization method are the economy of experimentation and simplicity of approach. In applying the method in the industry, several experiments are required. However, experimental costs may be prohibitive with several experiments. Therefore Taguchi method, which utilizes the minimum experiments, is suitable for solving the optimization problem. Moreover, in implementing the optimization process in the industry, the manager hands over the task to the operational floor workers. The degree of clarity and ease of actualizing the experimental design is a critical factor in the choice of the optimization method to hand over to the operational floor work. Thus, given these two viewpoints, the Taguchi method, which meets these two criteria, is chosen in the present study.

Furthermore, among the various optimization tools the Taguchi method stands out for its simplicity and high-value adding. Furthermore, the classical Taguchi method is a well-established technique. In the classical Taguchi method, the parameters are used directly in the evaluation of the signal-to-noise ratios after examining the orthogonal array information. A critical weakness of many studies optimizing using the Taguchi, Taguchi-Pareto and Taguchi-ABC methods to investigate the optimal parametric settings, rank and delta values of parameters is a lack of clarity on the parameters introduced for the orthogonal array choice. Should more aspects of other parameters be active in the signal-to-noise ratio evaluation than the parameters themselves? This means the aspect ratios may be an important consideration in the optimization process instead of direct parameters alone. The argument is that while investigating optimization of the weld bead geometric parameters in laser welding, the aspect ratios become relevant (Lei et al., 2019). Therefore, to understand precisely how the optimization values of the weld bead geometry in laser welding may be best evaluated researchers must draw from both direct parameters and aspect ratio of parameters.

In a research effort, the literature was searched and the prominent parameters, identified by Yang et al. (2012a) are the laser power, welding speed and wire feed speed. They developed optimization measures for the parameter using the Taguchi method. However, the viewpoint of the authors was very limited since it excludes the aspect ratios but only direct parameters. Notwithstanding, aspect ratios have been recently promoted by Oke and Adekoya (2022) in a maintenance engineering problem-solving situation. Significant improvement in the result that overshadows the use of direct parameters alone was reported. The argument is that despite the immense benefits of the aspect ratios, authors in the laser welding domain have reported, excluding their usage in the computation of optimal parametric settings.

However, to prevent a catastrophic occurrence in the sustainability of welding activities, the introduction of aspect ratios into the Taguchi technique's computation is compelling and worthwhile. Aspect ratios will promote a comprehensive discussion and treatment of all the possible configurations that laser welding parameters could be subjected to. The objective of this work is to optimize the parameters of the laser welding process. This was achieved by obtaining the optimal values of parameters, ranks and delta values for laser welding parameters using the Al-Mg-Mn-Zr-Er alloy sheets based on aspect ratio Taguchi method.

Furthermore, the significance of the study lies in that it offers a source of information to the policymakers in the industry where laser welding has a wide application. This includes the sanitary industry where welding of valves and showers, water pipe joints and joint reductions are made. Other industries include automobiles where sealing welding of the hydraulic tappet, ending cylinder gaskets and spark plug welding are predominantly conducted. Other cases are in the medical industry where stainless steel seals and structural parts of medical instruments are welded. Overall, the present study reinforces the optimization issue concerning weld bead geometry of laser welding using the Al-Mg-Mn-Zr-Er alloy. This optimization requirement is an alarming issue globally because of the increasingly difficult manufacturing activities where welding processes are difficult to sustain.

Considering the above discussions, this study is unique among the very few attempts at parametric selection and optimization in laser welding. It makes the following important contributions to the literature:

- It obtains aspect ratios for each parameter for the weld bead geometric laser welding process through the factor-level combination, to arrive at the optimal parametric setting for the combination of the aspect ratios.
- Three different scenarios of analysis are considered to strengthen the application and validate the aspect ratio Taguchi method.
- It ranks the aspect ratios of the weld bead geometric welding process parameters for the Al-Mg-Mn-Zr-Er alloy.
- The findings of this study validate the results of and the functionality of the method using experimental data from the literature.

2. LITERATURE REVIEW

2.1 Laser welding

Laser welding is a well-known contemporary process based on a workpiece that is illuminated through an excessive energy beam laser with a sharp temperature rise. It commences the welding process at the highest possible temperature and falls, subsequently to the lowest possible temperature. Here, the workpiece is melted and reconnected to create a stable bond. It gives the low bending strength and broad heat-affected zone of laser welded materials. The laser welding technique is gradually dominating welding activities in many industries. Laser welding has several benefits, including an attractive weld strength, which is a narrow laser weld having an outstanding depth-to-width quotient and superior strength. Moreover, the heat-affected zone is restricted. Additionally, laser has successfully welded carbon steel, stainless steel, aluminum, high-strength steel, dissimilar materials and titanium. These are used in diverse industries, including medical, automotive, electronics, hardware, glasses and sanitary. Consequently, there is an increase in the number of studies within the laser welding domain. However, researchers and practitioners are facing a danger of risk in economic decline. Practitioners and researchers present arbitrarily chosen parameters in component design. Unfortunately, intuition may fail in some situations; experience may not yield maximum results. Notwithstanding, quantitative measurement and methods that provide assessment are corrective tools to tackle the problem. In this regard, it is argued that optimization is the most suited tool to practice if laser welding is to be sustained for a long time.

2.2 The Al-Mg-Mn-Zr-Er alloy and processes

The material considered for analysis in this investigation is the Al-Mg-Mn-Zr-Er alloy, which consists of five major elements such as Al, Mg, Mn, Zr and Er. This alloy and its variants, which may contain less number of elements than these five elements have been studied under several processes, including the fatigue process (i.e. Al-Mg-Mn-Zr alloy by Lie et al., 2015). It has been used in deformation studies (i.e. Al-Zn-Mg-Er-Zr alloy by Wu et al., 2016). It is more largely used in welding studies, which is the subject of the present conversation. For example, welded joints were made by Wei et al. (2010) from Al-Mg-Mn-Zr and Al-Mg-Mn-Zr-Er alloys. The Al-Mg-Mn alloy (5083) was welded by Yan et al. (2013). Furthermore, the TIG and laser beam welding processes were applied to Al-Mg-Mn-Er alloy joints by Yang et al. (2012b). Thus, considering research activities in the literature, the focus of the review was on summarizing the progress made on the use of the Al-Mg-Mn-Zr-Er alloy using welding processes. It was found that the emphasis of most studies has been on these major themes. (1) the relationship between laser parameters, weld bead shape and temperature distribution was revealed by Dong et al. (2021) (2) Microstructural and mechanical property changes due to the temperature distribution in welding. Yang et al. (2012b), Yang et al. (2013), and Yang et al. (2011) are studies that propagate this idea. (3) The influence of introducing elements such as Er and Zr in modifying the microstructure and mechanical properties of alloys. Examples include Yang et al. (2013) (4) Conceptualization of optimization methods in controlling the parameters of welds. Examples are Yang et al. (2012a). (5) Precipitation and recrystallization behavior of the Al-Mg-Mn-Zr-Er alloy (Wu et al., 2017). Therefore, the subsequent discussions cover all these aspects although not segmented as above to ensure a brief discussion of the literature review. Thus, the details of the literature review are as follows.

Wei et al. (2010) welded the Al-Mg-Mn-Zr-Er alloy sheets using tungsten inert gas welding and examined the mechanical and microstructural properties of the joints. Yang et al. (2012) welded Al-Mg-Mn-Zr-Er samples by applying tungsten inert gas welding and observed their microstructural characterization. In another work, Yang et al. (2012) employed laser beam welding in comparison with the tungsten inert gas welding to join Al-4-7Mg-0.7Mn-0.3Er alloy plates and exploited the weld's microstructural and mechanical properties. Furthermore, Yang et al. (2013) joined the alloys of Al-Mg-Mn-Er-Zr and Al-Mg-Mn in laser welding and noticed tensile outcome enhancement as the Zr and Er were added to the Al-Mg-Mn alloy joint. In Lei et al. (2015), the fatigue crack propagation of Al-Mg-Mn-Zr alloys with erbium was examined. Furthermore, Zhang et al. (2015) used a fibre laser to weld a 20mm thick Al-Zn-Mg-Cu alloy with the filler wire to compare the Al-Mg-Mn alloy with Al-Mg-Mn-Zr-Er alloy welded joints.

Besides, Wu et al. (2016a) conducted isothermal compression tests on Al-Zn-Mg-Er-Zr alloy and developed constitutive models of the Arrhenius kind equation. The flow stress was reported to have been substantially influenced by the strain rate and deformation temperature, which also influenced the material constraints. It was concluded that the contributed constitutive equation can adequately represent the hot deformation characteristics of the Al-Zn-Mg-Er-Zr alloy. Also, Wu et al. (2016b) extended a previous study to examine a different range of temperature 573 to 733K instead of 300 to 460°C previously reported. Besides, in the alloy, Mn newly displaces the Zn to test Al-Mn-Mg-Er-Zr alloy under the strain rates of 0.001 to 10 s^{-1}. It was reported that two areas of high power dissipation efficiency occurred with the highest value at 653k $0.001s^{-1}$ while the peak values were revealed at above 37%. It was concluded that the occurrence of L12-structured Al_3(Er, Zr) particulates competently pinned the movement of dislocation and the boundary slide. Furthermore, Wu et al. (2017) studied the influences of homogenization handling on the precipitation characteristics of Al_3(Er, Zr) particulates and their influences on recrystallization confrontation in the Al-Zn-Mg-Er-Zr alloy. Most studies (Wei et al., 2010; Yang et al., 2012) deployed the tensile and hardness tests to explore the mechanical attributes of the alloy and the scanning electron microscope, optical microscope, energy-dispersive X-ray (EDX), and transmission electron microscopy (TEM) to examine the microstructural characteristics.

2.3 Welding parametric optimization and evaluation

Several interesting studies have been reported on the evaluation and optimization of welding parameters. Singh et al. (2024) adopted a multicriteria approach to analyze the parameters of the welding process with emphasis on the weld beads. Weld beads are seam deposits, which develop in welding at single steps. Closely related to this is the weld bead geometry describes the shape and size of the weld bead and indicates the melting and solidification process in welding. The authors uniquely compared the heat input and weld bead geometry in pulse metal-inert gas and cold metal transfer. It was noted that cold metal transfer welding samples exhibited more outstanding defect-free weld beads compared with pulse metal inert gas welding. Notwithstanding, the study did not consider the issue of the aspect ratio of parameters in the analysis. Besides, the welding conditions are different from those of laser welding. Moreover, Guo et al. (2022) evaluated welding parameters with a focus on the Taguchi method among other techniques utilized by the authors. A new integrated method called $TR_IF_mR_G$ through the clustering of the grey relational analysis, Taguchi method and other approaches was presented. In the work, the aspect ratios of parameters were ignored for the Taguchi approach used in the analysis. Furthermore, within the laser welding domain, Kumar et al. (2019) evaluated the process parameters of dissimilar laser welding concerning austenitic stainless steel (304L) coupled with carbon steel (st 47) and their relationship with weld bead geometry, among other characteristics of the welded joints. It was reported that recrystallized coarse grains were adjacent to the fusion zone. Also, a noticeable distance was observed between the nucleated grains and the fusion zone in the direction of carbon steel. Notwithstanding, the aspect ratio of the Taguchi method was to be considered in the evaluation. With the optimization context, Sathiya et al. (2011) established the optimal welding situations to expand productivity and reduce total operating costs while focusing on process parameters.

Although Taguchi's experimental design was the backbone of the analysis, the aspect was ignored in the computations. In the work comparison of the helium shielded weld metal and argon shielded weld metal was made as opposed to the laser welding considered in the present study. Bijivemula et al. (2022) joined AISI14130 alloy and AISI309 stainless steel of similar and dissimilar status using CO_2 laser beam welding while focusing on analyzing their process parameters. A novel whale optimization method was deployed for the optimization while the bead with microhardness was also of interest in the study. Though optimization was attempted in the study, it falls short of any aspect ratios of parameters in the analysis. Dey et al. (2023) conducted a numerical simulation to predict the parameters of laser welding when processing aluminum alloy 2024 and deploying the artificial neural network for the simulation. The weld geometry of the material was the emphasis of the predictive activities. Nonetheless, no mention or analysis of aspect ratios of parameters was made in the article. Still, in the same domain of prediction, Singh et al. (2014) predicted weld bead geometry in laser welding using a combination of genetic algorithms and neural networks. In the work, no information about the use of aspect ratios was mentioned or analyzed.

From the literature review conducted, the following gap can be stated:

1. The issue of how aspect ratios of laser welding parameters affect the weld beak parametric optimization using the Taguchi method has not been previously examined in the literature.
2. The particular influence of the reciprocal of parameters and their squares during the development of the orthogonal array to obtain the optimal parametric settings, ranks and delta values has been omitted in previous studies.
3. At present, a dearth of studies exists within the laser welding research area specifically on weld bead geometry. Hardly had studies considered. Taguchi optimization. The existing very few studies had not considered pre-modification or post-medication of the

orthogonal array frameworks for optimization gains.

4. The existing literature has failed to adequately tackle the influence of aspect ratios or its integration with direct parameters on the ranking and delta values of the weld bead geometric parameters in laser welding for the Al-Mg-Mn-Zr-Er alloy.

3. METHODOLOGY

This article focuses on the optimization of laser melding weld bead geometry for the Al-Mg-Mn-Zr-Er alloy. The optimization process is achieved by a set of steps of which a summary is given in what follows:

3.1 Procedure for implementing aspect ratio-based Taguchi method

The present authors introduced the aspect ratio-based Taguchi as a novel approach to compute the optimal values of the parameters while processing the Al-Mg-Mn-Zr-Er alloy with the laser welding process. The aspect ratio philosophy is a novel idea that introduces aspect ratios of the defined parameters as replacements of the direct parameters into the factor–level framework where the orthogonal arrays are defined and then converted to signal-to-noise ratios and subsequently the response table containing the optimal parametric settings, ranks and delta values of the parameters. These implementation steps for the aspect ratio-based Taguchi method are stated as follows:

Step 1: Establish the factors (Parameters) that should represent the laser welding process.

Step 2: Based on the parameters defined for the laser melding process, which are called direct parameters (factors) determine all the possible ratios of one parameter to the other for all the concerned parameters.

Step 3: For simplicity, limit the number of parameters to consider to the least possible to avoid complicated units being assigned to the parameters.

Step 4: Decide on the number of factors and levels for the parameters.

Step 5: Choose the orthogonal among that fits the chosen factors and levels combination.

Step 6: Develop the signal-to-noise computations based on one or more of the three criteria merely the smaller the better, the larger-the-better and nominal-the-based.

For the smaller-the- better criterion, Equation (1) is relevant (Oji and Oke, 2020):

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

Equation (2) is used when the criterion chosen is larger-the-better (Oji and Oke, 2020):

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

Equation (3) is used when the criterion of interest is nominal-the-best (Oji and Oke, 2020):

$$S/N = -10 \log_{10} y_i^2 / s^2 \quad (3)$$

where y_i is the performance characteristic of the i^{th} observed value

n is the trial number

s^2 is the variance of observations

Step 7: Obtain the averages of the signal-to-noise ratios and terms of the response table.

Step 8: Extract information on the optimal parametric settings, ranks and delta values from the response table.

4. RESULTS AND DISCUSSION

In this section the analysis of the result is presented for the different formulations considered in the work, the formulations regard the use of aspect ratios as parameters for the evaluation of optimal parametric settings. These aspect ratios are of three groups. In the first formulation, two parameters namely LP/WS and LP/WFR were considered while the formulation of the Second case is WS/LP and WS/WFR for the Third formulation the parameters are WFR/LP and WFR/WS. The collected data set addressed particular issues such as the optimal parametric settings, rank and delta value of the various parameters. The obtained results were then compared with those of Yang et al. (2012a) to establish concurrence or otherwise.

4.1 Formulation 1: LP/WS and LP/WFR

The analysis of the experimental data provided by Yang et al. (2012a) is presented in this section. From the original article, considering level 1, the values for laser power, weld speed, and welding feed speed are 2.4, 1.5, and 2, respectively. However, to obtain the aspect ratio of LP/WS for level 1, the value of 2.4 is divided by 1.5 to obtain 1.6. Likewise, by following this idea, values of 1.24 and 0.93 are obtained for levels 2 and 3, respectively. Furthermore, the same computations are made where laser power is treated as the numerator and welding feed speed as the denominator of an aspect ratio where 1.2, 0.52 and 0.35 are obtained as the respective values of the aspect ratio for levels 1, 2, and 3, respectively (Table 1). This is shown as the second and third columns in Table 1.

Table 1. Factors and levels for the laser welding parameters

Level	LP/WS	LP/WFR	WS/LP	WS/WFR	WFR/LP	WFR/WS
1	1.6	1.2	0.63	0.75	0.83	1.33
2	1.24	0.52	0.81	0.42	1.92	2.38
3	0.93	0.35	1.07	0.38	2.86	2.67

Note: LP – laser power, WS – welding speed, WFR – wire feed rate

The next step is to obtain an orthogonal array configuration that matches the combination of two parameters (i.e. LP/WS and LP/WFR) with three levels. Assistance was obtained using Minitab18 software with an input given as two factors by three levels. Here, under the 'Stat' function, the 'DOE' function was activated. This allowed exploring the Taguchi function and then a Taguchi design was created. This also provided the opportunity to choose the type of design that is compatible with two factors and three levels. The result is a matrix framework which consists of only entries 1 and 2. However, the present researcher has two options to choose from in obtaining the orthogonal arrays. The first option is L9 (3^2) which means that 9 rows and 2 columns will be created with 1 and 2 positioned as the level according to an organized structure. The second option is an L27 (3^2) orthogonal array which consists of 27 rows and 2 columns. In all, 54 entries of a mixture of 1 and 2 are presented in the second option. However, the present author chose L27 to permit more interactions with the parameters. Therefore, Table 2 shows the orthogonal arrays, translated orthogonal array and the signal-to-noise ratios.

It is important to explain the columns in Table 2: The first two columns after the serial number are the orthogonal arrays, which have 27 counts as serial numbers for formulation LP/WS and LP/WFR, respectively. The next two columns are the interpretations of the codes 1 and 2 of the orthogonal array into values. These are also for the formulations (WS/LP and WS/WFR) and (WFR/LP and WFR/WS). For an explanation, consider the value under serial number 1 for LP/WS, the value obtained is 1.6. How did we obtain the value? The answer is simply that code 1 under LP/WS will be interpreted from the factor-level table (Table 1) (level 1). The information here is that the equivalent of LP/WS for level 1, which is 1.5, should be written. This is how all the codes of 1 and 2 are translated into values. The next column is the SNR which is the short form of signal-to-noise ratio. For this instance, the smaller the better criterion is appropriate for the laser welding process while considering the weld bead geometry. It is therefore chosen for the current process.

Equation (1) which represents the smaller-the-better is used in the criterion. The result is shown as the signal-to-noise ratio. Furthermore, the response table is represented in Table 3 for LP/WS and LP/WFR. The question is how do we obtain this response table, is that for each parameter the average of the signal-to-noise ratio of those serial numbers that are concerned with the signal-to-noise ratio is taken (Table 3) to explain this last action consider filling the value -1.00525; How did we obtain this? It is noted that the parameter LP/WS is under level 1. What is done is to reach out to Table 2 and then trace the corresponding signal-to-noise ratio of level 1 which occurs from serial numbers 1-9. The corresponding signal-to-noise ratio is -1.24939 up to -1.59256 the average is -1.00525. In the same way, the average for the other five entries of levels 1-3 is computed. Next, each parameter with the highest and lowest values is considered and the difference is obtained as the delta value. In the case of the parameter LP/WS, the delta value is 3.837455. The delta value for LP/WFR is 2.628814. Now it is required to rank the two parameters, the one having the highest value is ranked 1^{ST} while is second parameter is ranked 2^{nd}. Therefore LP/WS is the first (best parameter) while LP/WFR is the 2^{nd} (worst parameter). Furthermore, the optimal parametric setting is chosen as LP/WS_1, LP/WFR_3. This is interpreted as 1.6 of LP/WS and 0.35 of LP/WFR when interpreted from the factor-level table.

Furthermore, in this work, the optimal parametric setting was computed for formulation where LP/WS and LP/WFR serve as parameters, and the optimal parametric setting is obtained as $LP/WS_{1,}$ LP/WFR_3 which is interpreted as 1.6kWmin/m of LP/WS and 0.35kWmin/m LP/WFR. In searching for the optimal parametric setting in Yang *et al*. (2012a), it was found that the author did not obtain the optimal parametric setting for the work. Although the Taguchi method was claimed to have been used, the perception utilized in the work was the use of the ANOVA method. Therefore the present authors used an L27 orthogonal array to evaluate the parameters for optimal parametric setting determination. It was established through our computation that the optimal parametric setting is $LP_1WS_1WFR_1$, which means 2.4 kW of laser power, 1.5m/min of welding speed and 2m/min of wire feed speed. Compared with what was obtained in our computation of formulation 1, there are bases for comparison because the units are different and the number of parameters is also different. Furthermore, in formulation 1, the corresponding delta values are 3.8375 and 2.6288. However, for the Taguchi method alone, using direct factor and three factors in the analysis, the delta values are obtained as 0.6047, 1.1093 and 6.85314 respective parameters of LP, WS, and WFR. If the averages of the delta values are compared, the following is the observation. For the Taguchi method Yang *et al*. (2012a), the average delta value is 2.8557 against 3.2332 when formulation 1 is used. The interesting information is that higher delta values imply a better result given by the method. Therefore formulation 1 with a higher delta value on average is better than direct factors alone. It is therefore suggested that in resource distribution analysis the aspect ratio parameters of LP/WS and LP/WFR should be preferably chosen for LP, WS, and WFR parameters. In the case of the Taguchi method Yang *et al*. (2012a) the position for LP, WS and WFR are 3^{rd}, 2^{nd}, and 1^{st} respectively. However, when formulation 1 is considered the position attained by LP/WS and LP/ WFR are 1^{st} and 2^{nd} respectively.

Table 2. Orthogonal arrays translated orthogonal arrays and signal-to-noise ratios

Sr. No.	LP/WS	LP/WFR	LP/WS	LP/WFR	SNR	WS/LP	WS/WFR	SNR	WFR/LP	WFR/WS	SNR
1	1	1	1.60	1.20	-1.2494	0.63	0.75	2.1992	0.83	1.33	4.8263
2	1	1	1.60	1.20	-1.2494	0.63	0.75	2.1992	0.83	1.33	4.8263
3	1	1	1.60	1.20	-1.2494	0.63	0.75	2.1992	0.83	1.33	4.8263
4	1	2	1.60	0.52	-0.1738	0.63	0.42	2.4311	0.83	2.38	4.7310
5	1	2	1.60	0.52	-0.1738	0.63	0.42	2.4311	0.83	2.38	4.7310
6	1	2	1.60	0.52	-0.1738	0.63	0.42	2.4311	0.83	2.38	4.7310
7	1	3	1.60	0.35	-1.5926	0.63	0.38	-3.8033	0.83	2.67	-4.2563
8	1	3	1.60	0.35	-1.5926	0.63	0.38	-3.8033	0.83	2.67	-4.2563
9	1	3	1.60	0.35	-1.5926	0.63	0.38	-3.8033	0.83	2.67	-4.2563
10	2	1	1.24	1.20	2.1304	0.81	0.75	5.1028	1.92	1.33	3.7421
11	2	1	1.24	1.20	2.1304	0.81	0.75	5.1028	1.92	1.33	3.7421
12	2	1	1.24	1.20	2.1304	0.81	0.75	5.1028	1.92	1.33	3.7421
13	2	2	1.24	0.52	4.9512	0.81	0.42	5.5674	1.92	2.38	3.6677
14	2	2	1.24	0.52	4.9512	0.81	0.42	5.5674	1.92	2.38	3.6677
15	2	2	1.24	0.52	4.9512	0.81	0.42	5.5674	1.92	2.38	3.6677
16	2	3	1.24	0.35	1.4150	0.81	0.38	-3.2363	1.92	2.67	-4.4058
17	2	3	1.24	0.35	1.4150	0.81	0.38	-3.2363	1.92	2.67	-4.4058
18	2	3	1.24	0.35	1.4150	0.81	0.38	-3.2363	1.92	2.67	-4.4058
19	3	1	0.93	1.20	1.4897	1.07	0.75	-1.2022	2.86	1.33	-4.4207
20	3	1	0.93	1.20	1.4897	1.07	0.75	-1.2022	2.86	1.33	-4.4207
21	3	1	0.93	1.20	1.4897	1.07	0.75	-1.2022	2.86	1.33	-4.4207
22	3	2	0.93	0.52	3.7973	1.07	0.42	-1.0978	2.86	2.38	-4.4321
23	3	2	0.93	0.52	3.7973	1.07	0.42	-1.0978	2.86	2.38	-4.4321
24	3	2	0.93	0.52	3.7973	1.07	0.42	-1.0978	2.86	2.38	-4.4321
25	3	3	0.93	0.35	0.8657	1.07	0.38	-4.9373	2.86	2.67	-7.0781
26	3	3	0.93	0.35	0.8657	1.07	0.38	-4.9373	2.86	2.67	-7.0781
27	3	3	0.93	0.35	0.8657	1.07	0.38	-4.9373	2.86	2.67	-7.0781

Note: The orthogonal array for all the formulations i.e. for (LP/WS and LP/WFR), (WS/LP and WS/WFR) and (WFR/LP and WFR/WS) is the same

Table 3. Response table for (LP/WS and LP/ WFR), (WS/LP and WS/ WFR) and (WFR/LP and WFR /WS)

		Formulation 1		Formulation 2		Formulation 3	
Level		LP/WS	LP/WFR	WS/LP	WS/WFR	WFR /LP	WFR /WS
	1	-1.0053*	0.7902	0.2757	2.0333	1.7670	1.3826
	2	2.8322	2.8582	2.4780	2.3002	1.0013	1.3222
	3	2.0509	0.2294*	-2.4124	-3.9923	-5.3103	-5.2468
Delta		3.8375	2.6288	4.8904	6.2925	7.0773	6.6293
Ranking		**1st**	**2nd**	**2nd**	**1st**	**1st**	**2nd**

4.2 Formulation 2: WS/LP and WS/LP

Similar to how formulation 1 was made, the development for formulation 2 proceeded. However to obtain the aspect ratio of LP/WS for level 1 the value of 2.6 is divided by 2.1 to obtain 0.63 likewise by following this idea, values of 0.81 and 1.07 are obtained for levels 2 and 3 respectively. Furthermore, the same computations are made where laser power is treated as the numerator and welding feed speed as the denominator of an aspect ratio where 0.75, 0.42 and 0.38 are obtained as the respective values of the aspect ratio for levels 1, 2, and 3 respectively (Table 2). This is shown in the second and third columns in Table 1. The next step is to obtain an orthogonal array configuration that matches the combination of two parameters (i.e. WS/LP and WS/WFR) with three levels. Minitab18 software was used for analyzing two-factor and three-levels for orthogonal array selection. Here under the 'Stat' function, the 'DOE' function was activated this allowed exploring the Taguchi function and then a Taguchi design was created. This provided the opportunity to choose the type of design that is compatible with two factors and three) levels the result is a matrix framework which consists of only entries 1 and 2. However, the present researcher has two in obtaining the orthogonal arrays. The first option is L9 (3^2) which means that 9 rows and 2 columns will be created with 1 and 2 positioned as the level according to an organized structure.

The second option is an L27 (3^2) orthogonal array which consists of 27 rows and 2 columns. In all, 54 entries of a mixture of 1 and 2 are presented. However, the present authors chose L27 to permit more interactions with the parameters. Therefore, Table 2 shows the orthogonal arrays translated orthogonal array and the signal-to-noise ratio. It is important to explain the columns in Table 2, the first–two columns are the orthogonal array which has 27 counts as serial numbers for LP/WS and LP/WFR respectively the next two columns are the interpretation of the coded 1 and 2 of the orthogonal array into value. These are also for the parameters WS/LP, WS/WFR and WS/LP and WS/WFR. For an explanation consider the value under serial number 1 for WS/LP the value obtained is 0.63. How do we get the value, simply that code 1 under WS/LP will be interpreted from the factor and level (level 1) the information here is that the equivalent of LP/WS for level 1 which is 0.63 should be written. This is how all the codes of 1 and 2 are translated into values. The next column is the SNR which is the short-form signal-to-noise ratio. For this instance the smaller the better criterion is appropriate for the laser welding process while considering the weld bead geometry. It is therefore chosen for the current process, Equation 1 which represents the smaller the better is used in the criterion. The result is shown as the signal-to-noise ratio. Furthermore, the response table is represented in Table 3 for LP/WS and LP/WFR. The question is how do we obtain this response table, is that for each parameter the average of the signal-to-noise ratio of those serial numbers that are concerned with the signal-to-noise ratio is taken (Table 3) to explain this last action consider filling the value 0.27567; How did we obtain this? It is noted that the parameter WS/LP is under level 1. What is done is to reach out to Table 2 and then trace the corresponding signal-to-noise ratio of level 1 which occurs from serial numbers 1-9. The corresponding signal-to-noise ratio is 2.19923 up to -3.80332 the average is 0.27567. in the same way, the average for the other five entries of levels 1-3 is computed. Next, for each parameter, the highest and lower values are considered and the difference is obtained as the delta value. In the case of the parameter WS/LP, the delta value is 4.89038. The delta value for WS/WFR is 6.29252. Now, it is required to rank the two (2) parameters, the one having the highest value is ranked 1st while is second parameter is ranked 2nd. Therefore WS/WFR is the first (best parameter) while WS/LP is the 2nd (worst parameter). Furthermore, the optimal parametric setting is chosen as WS/WFR_1, WS/LP_3. This is interpreted as 0.75 of WS/WFR and 1.07 of WS/LP when interpreted from the factor-level table.

For formulation 2, the optimal parametric setting is $WS/LP_3WS/WFR_3$ which is interpreted as 1.07m/kWmin of WS/LP_3 and 0.38 of WS/WFR. As acknowledged in formulation, Yang et al. (2012a) failed to specify the optimal parametric setting of the problem. However, when computing based on the L27 orthogonal array, the obtained result was compared with formation 2 where the parameters are the aspect ratio WS/LP and WS/WFR. Besides, it was ascertained that the average delta value for the Taguchi method Yang et al (2012a) is 2.8557. However, while examining the delta values of the parameters in formulation 2 it is 5.59145. This value is higher than the average delta value provided by Yang *et al*. (2012.), formulation 2 is superior to it. Furthermore, for the ranking of parameters, WS/LP is ranked 1st while WS/WFR is ranked 2nd.

4.3 Formulation 3: WFR/LP and WFR/WS

The analysis of the experimental data provided by Yang *et al*. (2012a) is presented in this section. From the original article, considering level 1 the values for laser power, weld speed, and welding feed speed are 2, 5, and 8 respectively. However to obtain the aspect ratio of LP/WS for level 1 the value of 2 is divided by 2.4 to obtain 0.83 likewise by following this idea, values of 1.92 and 2.86 are obtained for levels 2 and 3 respectively. Furthermore, the same computations are made where laser power is treated as the numerator and welding feed speed as the denominator of an aspect ratio where 1.33, 2.38 and 2.67 are obtained as the respective values of the aspect ratio for levels 1, 2, and 3 respectively (Table 2). This is shown in the second and third columns in Table 1. The next step is to obtain an orthogonal array configuration that matches the combination of two parameters (i.e. WFR/LP and WFR/WS) with three levels. Assistance was obtained using Minitab18 software with input given as two factors by three levels. Here under the 'Stat' function, the 'DOE' function was activated this allowed exploring the Taguchi function and then a Taguchi design was created. This provided the opportunity to choose the type of design that is compatible with two factors and three levels the result is a matrix framework which consists of only entries 1 and 2. However, the present researcher has two in obtaining the orthogonal arrays. The first option is L9 (3^2) which means that 9 rows and 2 columns will be created with 1 and 2 positioned as the level according to an organized structure.

The second option is an L27 (3^2) orthogonal array which consists of 27 rows and 2 columns. In all, 54 entries of a mixture of 1 and 2 are presented. However, the present author chose L27 to permit more interaction with the parameters. Therefore Table 2 shows the orthogonal arrays translated orthogonal array and the signal-to-noise ratio. It is important to explain the columns in Table 2, the first–two columns are the orthogonal array which has 27 counts as serial numbers for LP/WS and LP/WFR respectively the next two columns are the interpretation of the coded 1 and 2 of the orthogonal array into value. These are also for the parameters WFR/LP, WFR/WS, WFR/LP and WFR/WS. For an explanation consider the value under serial number 1 for WFR/LP the value obtained is 0.83. How do we get the value, simply that code 1 under WS/LP will be interpreted from the factor and level (level 1) the information here is that the equivalent of LP/WS for level 1 which is 0.83 should be written. This is how all the codes of 1 and 2 are translated into values. The next column is the SNR which is the short form of signal-to-noise ratio. For this instance the smaller the better criterion is appropriate for the laser welding process while considering the weld bead geometry. It is therefore chosen for the current process, equation 1 which represents the smaller the better is used in the criterion. The result is shown as the signal-to-noise ratio. Furthermore, the response table is represented in Table 3 for LP/WS and LP/WFR. The question is how do we obtain this response table, is that for each parameter the average of the signal-to-noise ratio of those serial numbers that are concerned with the signal-to-noise ratio is taken (Table 3) to explain this last action consider filling the value 1.76699; How did we obtain this? It is noted that the parameter WS/LP is under level 1. What is done is to reach out to Table 2 and then trace the corresponding signal-to-noise ratio of level 1 which occurs from serial numbers 1-9. The corresponding signal-to-noise ratios are 4.82628132 up to -4.25632024 the average is 1.76699. in the same way, the average for the other five entries of levels 1-3 is computed. Next, for each parameter, the highest and lower values are considered and the difference is obtained as the delta value. In the case of the parameter WFR/LP, the delta value is 7.077287. The delta value for WFR/WS is 6.62932. Now it is required to rank the two parameters, the one having the highest value is ranked 1st while is second parameter is ranked 2nd. Therefore WFR/LP is the first (best parameter) while WFR/WS is the 2nd (worst parameter). Furthermore, the optimal parametric setting is chosen as WFR/LP_1, WFR/WS_3. This is interpreted as 0.83 of WFR/LP and 2.67 of WFR/WS when interpreted from the factor-level table.

For this formulation, the optimal parametric setting is WFR/LP_3 WFR/WS_3, which is interpreted as 2.86m/kWmin of WFR/LP and 2.67 of WFR/WS. The corresponding delta values are 7.0773 and 6.6293 for the respective parameters of WFR/LP and WFR/WS. The average of this delta value is 6.8533 when this average is compared with the average delta value using Yang et al. (2012a). Furthermore, the positions in formulation 3 are 1st and 2nd positions for the respective parameters of WFR/LP and WFR/WS.

4.4 Implications of the research

The findings of this study have several advantages and the industry can take advantage of them from various perspectives. First, managers of the laser welding industry desiring to produce quality welded joints could deploy the values obtained from the optimal parametric settings to set boundaries (lower and upper) with which the weld quality could be compared in practice. The attainment or non-attainment of quality standards by this means will distinguish staff by competence levels. Highly competent individuals who consistently attain targets may be redeployed to more sensitive areas of the welding process while less competent individuals trained on the same job or scheduled for other less sensitive jobs. By this, a balance in the deployment of manpower will be attained. Second, aspect ratios that are most sensitive may be distinguished from those having low sensitivity. This could be used as information to decide on what parameter (aspect ratios) the greatest and least resources in the laser welding process should be allocated for their judicious usage in the welding process. Moreover, the results of the method may be useful as a negotiating tool for the management of the laser welding industry to negotiate for reward (i.e. productivity improvement scheme) for the worker if certain thresholds are considered.

4. CONCLUSIONS

This work contributes to the literature by offering a robust method of modified Taguchi with direct factors and aspect ratios for the optimization of the weld bead geometry for Al-Mg-Mn-Zr-Er alloy. The method optimizes parametric settings, which are defined for each parameter. Precisely, this paper differs from previous studies (i.e. Yang et al., 2012a) where the Taguchi method has been applied as an optimization framework. The difference is that the direct parameters of laser power, welding speed and welding feed speed are treated as aspect ratios involving the following: laser power-welding speed ratio, laser power-welding feed rate ratio, quotients involving welding speed and laser power, welding speed and welding feed rate, welding feed rate and laser power, welding feed rate and welding speed. Then, a robust aspect ratio-based Taguchi method that handles the dimensional characteristics of one ratio to the other is proposed. This aspect-based Taguchi configuration is then introduced with the levels to obtain orthogonal arrays that are processed into signal-to-noise ratio based on one or more of three criteria. This involves smaller-the-better, larger-the-better and nominal-the-best.

Furthermore, the following areas of future research will contribute to the present research area. First, sensitivity analysis is a useful tool for studying the behavior of parameters. Hence, this tool could be deployed to understand how the aspect ratios behave in isolation or combination with direct parameters of the weld bead geometry. The requirement to actualize sensitivity analysis is the data on parametric values and criteria values. The earlier may be obtained from experiments while the latter could be calculated from the signal-to-noise ratios of the parameters. Second, parametric values, delta and ranks may be simulated and analyzed using the Monte-Carlo simulation method with or without hybrids and appendages. Third, the responses of the Al-Mg-Mn-Zr-Er alloy to the hybrid method of the Taguchi method and fuzzy analytic hierarchy method need to be investigated in laser welding research.

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