Applying Multi-Criteria Approaches to the Weld Bead Geometry Problem in Laser Welding With Filler Wire Process Using the Al-Mg-Mn-Zr-Er Alloy Sheet

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Abstract. *Al-Mg-Mn-Zr-Er alloy sheet is a prominent industrial material used by the automotive and aerospace industries. Yet little is known about which parameters substantially affect the weld bead geometry in laser welding. This article establishes the most influential process parameters in laser welding with filler wire process on the Al-Mg-Mn-Zr-Er alloy sheets focusing on laser power, welding speed, wire feed speed parameters. The data obtained from a paper was used for analysis. Five methods were compared, namely analytic hierarchy process (AHP) method, fuzzy analytic hierarchy process (FAHP) method, best-worst method, entropy method and criteria importance through inter-criteria correlation (CRITIC) method. The arithmetic mean (AM) method and the root mean square (RMS) method were used to compare the results of the five methods. Using the AM method, the FAHP method is the best (AM, 0.3367), the entropy method is the second position (AM, 0.3337) and the three methods of AHP, best worst and CRITIC (AM, 0.3333 each) were placed in the third position. Besides, for the RMS method, the entropy and FAHP methods were the first and second positions with the RMS values of 0.2094 and 0.1954, respectively. The third to the last positions were allocated to best worst (RMS, 0.1948), AHP (RMS, 0.1894) and CRITIC (RMS, 0.1274), respectively. Consequently, the FAHP method is the best and recommended to develop cost reduction strategies in the workshop. The novelty of this article is the application of five multicriteria methods, namely AHP, FAHP, best-worst, entropy and CRITIC to the Al-Mg-Mn-Zr-Er alloy sheets.*

Received by	20 August 2021
Revised by	26 October 2021
Accepted by	6 March 2022

Keywords:

laser welding, selection, process parameters, multicriteria analysis

1. Introduction

After At present, the invention of the laser is being celebrated in its 61st anniversary worldwide [1]. Interestingly, from the introduction of lasers to the industry to date, tremendous success has been reported in the global usage of lasers for materials processing [1]. This success has been attributed to the huge development of the output of laser power that enables multiple materials processing tasks to cope with the demand on product features by the industries and their customers [2]. Consequently, lasers have been positioned as useful and undeniably developmental industrial tools in diverse material processing tasks [1].

Furthermore, globally, the market for laser welding and cutting robots in 2020 was estimated at 518.52 million USD and is expected to grow at 8.6% from 2020 to 2027 [3]. Thus there is a great potential for laser welding penetration worldwide and substantial opportunities for a wider technological scope and enhanced product quality attainment in the industry [4],[5]. Laser welding describes a welding method that applies laser's energy heat source to join metal pieces or thermoplastics with a concentrated heat source that directs narrow but deep welds at high welding speed [4]-[6]. The workpiece is often located under a microscope while the wire is hand-gripped. The about-to-be-welded sample is examined using cross wires in the ocular. The wire (filler object) is afterwards positioned on the location to be welded while the wire melts by the impact of the laser pulse as well as the base object beneath. Then the wire and the object are welded but the weld bead is central to this welding system [4]-[5].

A weld bead describes a laser welding deposit of the filler material in a welding pass [5]. Several fusion deficiencies in weld failures have been reported due to little or poor interest in the shape and size of weld beads. Thus, significant attention should be directed to weld beads to achieve good welds known to be uniform and straight, devoid of holes, cracks, slags, craters, dips and not extremely thin [7]. The adequate weld bead shape is a function of parameters, including laser line power that explains the heat energy delivered to the base plate assessed in a unit length of weld, wire feed speed and welding speed [5].

Consequently, weld bead geometry is a critical issue in the delivery of acceptable welded joints [7]-[14]. However, some existing studies advocate for more intensive analysis of weld bead geometry as it is influenced by welding parameters [7],[9]. Unfortunately, the literature review reveals that extremely meagre attention was made to study the effects of process parameters such as laser power, welding speed, feed speed in laser welding with filter wire process [8]. Furthermore, for the unique joints of Al-Mg-Mn-Zr-Er alloy sheets, almost no existing studies have been reported on multicriteria studies to choose the best parameter in laser welding with filler wire process [15]-[21]. Besides, no comparisons among several multicriteria methods have been documented in the present context of laser welding of Al-Mg-Mn-Zr-Er alloy sheets.

Therefore, this study compares the optimisation technique on the weld bead geometry, involving process parameters, using the analytic hierarchy process (AHP) method, fuzzy analytic hierarchy process (FAHP) method, best-worst method, entropy method and criteria importance through inter-criteria correlation (CRITIC), to choose the best parameter among laser power, welding speed, and feed speed. The data obtained from the literature are analyzed and used to validate the approach presented in this study. It is expected that the results obtainable from this research will enhance planning activities in the laser welding workshop and activities. The principal contributions of this study may be summed up as follows:

1. This study is the first to compare the performance of the AHP, FAHP, entropy, BWM and CRITIC methods for the laser welding process parametric selection of the Al-Mg-Mn-Zr-Er alloy.
2. For the parametric selection problem of the Al-Mg-Mn-Zr alloy, the subjective features of the AHP, FAHP and BWM and individual data-oriented assessments of the objective weighing methods of the CRITIC and entropy methods, the complete methods (all the five approaches) have been adopted.
3. Since a sole method of multicriteria analysis seems inappropriate to assure a precise choice, five multicriteria approaches were used to rank the laser welding process parametric factors.
4. A rare approach involving the arithmetic mean method and the root mean square method for the comparative analysis of the results is presented.

2. Literature Review

2.1 Welded Joints Involving Al-Mg-Mn-Zr-Er Alloys

While welding, the laser welding operator is constantly associated with airborne particles (or fumes), vibrations, moving mechanical parts, the danger of electric shock, noise, caustic chemicals (or toxic) substances among others. Despite these challenges, the operator must endeavour to produce high-quality welds by selecting proper fixtures, cutting and welding programmes to achieve the system's goals. But the goal attainment largely depends on the weld bead geometry. Although the literature has reported on weld bead geometry, consideration concerning the Al-Mg-Mn-Zr-Er alloy sheets is poorly discussed. But the Al-Mg-Mn-Zr-Er alloy sheets, which are Al-Mg-Mn-Zr with erbium are attracted by the industry for their ability to enhance machinability and lower the rate of fatigue crack propagations. The precipitate of Al_3(Er, Zr) in the Al-Mg-Mn-Zr-Er alloy sheets may draw the Al, Zn and Mg elements in heterogeneous nucleation and significantly lower the large brittle second phase of the Al_3Mg_2 compound, which exists at the grain boundary [18].

In this article, parameters such as laser power, welding speed, feed speed in the laser welding of Al-Mg-Mn-Zr-Er alloy sheets to select the best parameter with filler wire process. The optimisation technique was compared using analytic hierarchy process (AHP), method, fuzzy analytic hierarchy (FAHP) method, best-worst method, entropy method and criteria importance through inter-criteria correlation (CRITIC) method. Consequently, this article is novel with the novelty being about the application of five multicriteria methods, namely the AHP, FAHP, best-worst, entropy and CRITIC to the Al-Mg-Mn-Zr-Er alloy sheets. Subsequently, a literature review to support the material analyzed is presented.

Wei et al. [15] welded the Al-Mg-Mn-Zr-Er alloy sheets using the tungsten inert gas welding and examine the mechanical and microstructural properties of the joints. The joints revealed a growth in tensile strength by 57MPa while the weld joint coefficient grew to 0.8 as the application of Al-Mg-Mn-Zr-Er welding wire was made to fill the welds. Furthermore, the strengthening of grain refinement was experienced. Yang et al. [22] welded Al-Mg-Mn-Zr-Er samples by applying tungsten inert gas welding and observed their microstructural characterization. Furthermore, hardness and tensile experiments were conducted on the samples. A 72% ultimate tensile strength of the joint relative to the base metal was obtained. It was concluded that tungsten inert gas welding is adequate to weld the newly developed Er-enclosing aluminium alloys. In another work, Yang et al. [16] 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. The tensile strength of the laser beam welding exceeded that of the tungsten inert gas welding by 10%. Besides, the superiority of the laser beam welding was demonstrated in smaller equiaxed grains in the fusion zone, significant growth of nucleation rate and the burning loss rates of magnesium.

Furthermore, Yang et al. [17] joined the alloys of Al-Mg-Mn-Er-Zr and Al-Mg-Mn in laser welding to examine the effects of Zr and Er addition on the properties (mechanical, microhardness and microstructure) of the Al-Mg-Mn alloy welded joints. Improvement in the tensile outcome through the ultimate tensile strength and the yield strength evaluation was noticed as the Zr and Er were added to the Al-Mg-Mn alloy joint. The driving force for this enhancement was attributed to grain refining strengthening. In Lei et al. [18], the fatigue crack propagation of Al-Mg-Mn-Zr alloys with erbium was examined. It was reported that the Al_3(Er-Zr) precipitate could lower the stress concentration occurring at the grain boundary to reduce fatigue crack propagation. Furthermore, Zhang et al. [23] 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. Success was reported on the fine grains outcome of the weld.

Besides, Wu et al. [19] 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. [20] 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, Kn newly displaces the Zn to test Al-Kn-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. [24] 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 was studied using multiple homogenization handlings. The authors reported finer particulates size, superior density and volume ratio of the Al_3(Er, Zr) particulates in 75% of the homogenization handlings. It was concluded that the double-phase homogenized cum ram heating homogenized samples exhibited substantially reduced recrystallized proportion weighed against the traditional one-phase homogenized specimens.

Pros and Cons of the Al-Mg-Mn-Zr-Er Literature

The Al-Mg-Mn-Zr-Er alloy is a new alloy that provides substantial product diversification opportunities in the aerospace and automobile industries. In this article, some positive and negative viewpoints on the studies of Al-Mg-Mn-Zr-Er alloy are presented. Perhaps the strongest argument to study the Al-Mg-Mn-Zr-Er alloy may be obtained from the need to understand its microstructural and mechanical characterization. Most studies [15]-[16],[22] 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. In the first case, the ultimate tensile strength of joints indicates the structural integrity of the joint relative to the base metal. For the microstructural examinations, the idea was to examine the fusion boundary and understand the quality of the particles between the base metal and the fusion zone. Though a perfect understanding is yet to be attained concerning the microstructural and mechanical properties of the Al-Mg-Mn-Zr-Er alloy, proponents of this idea continue to research towards its fuller realization. Advocates of the physical property exploration of the Al-Mg-Mn-Zr-Er alloy also pursue the goal of enhancing recrystallization resistance of the alloy where the minimization of the width regarding precipitation fee zone around the grain boundary to enhance the strengthening effect of the alloy. However, many agree that excessive pursuit of the physical attributes of the microstructural and mechanical properties of Al-Mg-Mn-Zr-Er alloy can be a negative experience since it is at the expense of other aspects of research concerning the Al-Mg-Mn-Zr-Er alloy such as the economics of the laser welding process parameters with filler wire process. A study of the laser welding process parameters offers a deep insight into resource deployment and control in association with the process parameters.

Aravind et al. [25] found that VIKOR multicriteria method was useful in the identification of the most important laser welding parameters with the Ti6Al4V as the work material thereby enhancing process organization. However, various multicriteria methods that have been proved to be effective in engineering decision making are available in the literature. Some five key methods that warrants testing in the laser welding processing of the Al-Mg-Mn-Zr-Er alloy are the AHP method, FAHP method, best-worst method, entropy method and CRITIC method. However, there is little attention paid to the use of these methods in the perspective of laser welding of process parameters concerning the Al-Mg-Mn-Zr-Er alloy. Nonetheless, it is thought that by using these methods in the proposed context, more balanced literature on the Al-Mg-Mn-Zr-Er alloy and the wider laser welding literature is possible.

2.2 Weld Bead Geometry and Laser Welding Process

In a study, Yang et al. [8] deployed the Taguchi method to optimise the chosen welding parameters of welding speed, laser power and wire feed rate while the weld quality is the response variable. Nevertheless, the study concludes that the welding speed has the greatest impact on the weld quality while the least impact on the weld quality was felt by the laser power. Furthermore, Bidi et al. [9] contributed another work to the model bead geometry optimisation. Besides, the considered response is the weld bend geometry while the principal parameter is the H/L ratio. In another work, the heat input concerning the bead geometry is the focal point of discussion by Tayier et al. [14]. The authors welded the zincalume (G550) materials using the MIG and LBM processes. Nonetheless, the outcome of their study is that the wire speed (MIG) and the welding speed (LBW) yielded 0.6089 and 0.0221 kJ/min of energy at the welding speed and wire speed of 16mm/sec and 3 m/min, respectively.

Besides, Choudhury and Chandrarasekaran [10] conducted gas tungsten are welding experiments using the Inconel 825 as the work material but centred attention on the optimization of weld bead attributes while deploying the Box-Behnken design for the computational aspects. The parameters considered in the article are the gas flow rate welding speed, welding current, and are length. Nonetheless, an important result of the study is that for the responses chosen, the welding current was the most influential parameter in the gas tungsten arc welding process. The second parameter of importance in the process is the welding speed. In another article, Nabavi et al. [13] instituted physical-oriented contour plots to estimate the pattern of weld behaviour by analyzing the power density and heat input. The weld bead characteristics are the main focus of the study. Nonetheless, the article concludes that a higher penetration-to-width proportion yields elevated fracture load. Furthermore, Khan et al. [26] elaborated on the weld bead geometry but considered a different route in analysis by analyzing the influence of laser beam defocusing on the weld geometry with emphasis on welding 22MnB5 grade of press-hardened steel. The considered responses are the defects, including cyclic humping, porosity, and weld concavity. The important conclusion of the article is that the developed framework showed competence to predict the molten weld pool geometry.

Yet in another work, Huang et al. [27] offered a new approach to optimizing the weld strength of the steel-PMMA joint using the innovative Taguchi method. The principal result of the study is that the joint efficiency attained 70% of the base PMMA, which was not previously discussed in the literature. In another research, Hietala et al. [28] optimized the tensile-shear strength of lap joints built up by laser welding. The ARS-600 steel was thoroughly analyzed using diverse welding parameters and patterns of welds. In another article, the development mechanism of the weld bead and temperature field close to the fusion region was examined. The study concludes that the influence of the nozzle distance on the temperature field was more compared with the laser power and welding speed. In a study, Aravind et al. [25] optimized the welding parameters while welding Ti6Al4V by the combined use of the VIKOR and Taguchi method. Nonetheless, the study concludes that the 7th experimental trial yielded the optimized parameters at the power, speed, shielding gas flow rate of 1.3kW, 0.3m/min and 20L/min, respectively. Besides, Horvath et al. [12] established an approach to weld bead profile development with a focus on multi-pass welding. Kannan et al. [29] employed Deng's similarity oriented method jointly with the entropy weight approach and Taguchi orthogonal matrix of L9 for the bead-on-plate welding of Nitinol shape memory alloy. The parameters considered are the shielding gas blown distance, laser power, welding speed, and focus position.

Pros and Cons of Weld Bead Geometry Literature

Weld bead geometry is a significant focal point of most research on welding efficiency improvement. As with many other determinants of welding efficiency, there have been doubts and research discussions on the present direction of research on weld bead geometry, especially as it relates to the laser welding process. Also, there have been promotion and support for the current emphasis of research on weld bead geometry regarding the laser welding process. Current weld bead geometry research advocates for methods to create the least weld bead width as well as the fusion zone area as one of the strongest research aspects. Researchers involved in weld bead geometry discussions have a very strong drive regarding the positive outcomes that studies have brought to enhancing the quality of weld beads and consequently the structural integrity of the welds. Since the heat input into the welded joints could be controlled during operations. Thus, weld bead geometry studies are popular but some critics have been raised by other researchers that question the probable negative influences of channeling many efforts on weld bead geometry research at the expense of other aspects with some economic benefits to the process.

Criticisms of almost sole investment of research efforts on weld bead geometry in laser welding are vast and they have advanced several reasons it could be detrimental to the healthy development of the laser welding literature. One such argument is that the influence of process parameters on the welding quality is downplayed and the order of importance of parameters, which may guide economic decisions for the laser welding process is not known. Without understanding the prioritization of process parameters while the optimisation of the weld bead geometry is the focus judicious distribution of scarce laser welding process resources may not be achieved. This result in conflicts among operators and the labour union may be forced to intervene. However, while supporting this new, Yang et al. [8] offered a Taguchi approach and considered the delta values to determine the prioritized parameters. By furthering this approach with some key multicriteria methods of AHP method, FAHP method, best-worst method, entropy method and CRTIC method and evolving a comparison is perceived to correct the present knowledge deficiency in the literature concerning the selection of process parameters. Next, the summary of the literature is given in Table 1.

Furthermore, motivated by Şahin [48] in the diverse choice of multicriteria methods to solve a problem and rank alternatives, this article chooses five multicriteria methods in this study. These methods are the analytics hierarchy process (AHP) method, fuzzy analytic hierarchy process (FAHP) method, entropy method, best waist method and the criteria importance through intercriteria correlation (CRITIC). The principal reasons which aided the selection of these methods are explained as follows. First, the chosen methods are commonly used by researchers and by providing enough and new details about their utility will enable works is in the area to expand knowledge and practice by replicating the methods in different contexts. For example, process engineers and researchers in heavy industrial situations will find the methods useful. They may be applied to operations involving the production of exhaust heat shields, industrial oven doors, stainless steel appliances and drive train gears. Second, the chosen methods are classified by different groups and follow various steps [48]. For instance, a convenient grouping could be a method with or without the preferences of the decision-makers. Out of the five methods chosen, two methods need the inputs of the decision-makers. These methods are the AHP method and the FAHP method. These methods are influenced by the inputs of the decision-makers. However, the other three methods are subjective, namely the CRITIC, entropy method and the best worst method. Still, on different family groupings [48], the choice of the five methods considered in this article is based on the different groupings of the methods as tree diagrams intensive and algorithmic intensive. In this context, the AHP method and the FAHP method are tree diagram intensive while the entropy, best-worst method and CRITIC method are algorithmic intensive methods.

Consequently, it is more reasonable to employ multiple methods to assess the results of the laser welding process problem than to adopt only a method [48]. To support this argument, Şahin [48] and Ozernoy [49] admitted that it is challenging to obtain a perfect multicriteria decision-making method that could create the premeditated results for all problems. To support a diversity of choice of methods for testing, Ishizaka and Siraj [50] strongly suggested the adoption of multiple multicriteria decision making approaches to enhance the accuracy of the outcomes for a particular problem. This idea was however supported by Şahin [48] with an application to energy and electricity generation in Turkey. Furthermore, Haddad and Sanders [51] and Mosadeghi et al. [52] emphasized the adoption of multiple multicriteria decision-making techniques to reduce uncertainties in the analysis. Thus, based on these literature viewpoints, five multicriteria methods were adopted in the present article.

S/N	Author and year	Domain of study	Work materials	Key parameters	Adopted method	Output (response(s))	Result(s)
1	Yang et al. [8]	Optimization of weld bead geometry	Al-Mg alloy	Laser power, welding speed and wire feed rate	Taguchi approach, laser welding	Weld quality	Optimal laser power is 2.4kW, welding speed of 3m/min, wire feed rate of 2m/min
2	Bidi et al. [9]	Weld bead geometry optimisation	Chamfer	Lateral penetration, H/L ratio	Hybrid laser-MAG welding	Productivity, reliability, experimental design	Total lateral penetration was more than 0.4 mm and a H/L ratio was less than 0.6
3	Tayier et al. [14]	Heat input energy	Zincalume steel	Bead width, depth of penetration, welding speed, wire speed	Metal inert gas (MIG), laser beam welding (LBW), Taguchi method, ANOVA	Bead geometry, heat input energy	In MIG and LBW, grain growths were noted. Bead width and depth of penetration of 2.92 mm and 1.26 mm, respectively, yielded reduced welding speed and elevated wire speed in MIG and LBW processes, respectively.
4	Choudhury and Chandrasekaran [10]	Optimisation of weld bead characteristics	Inconel 825	Welding current, welding speed, arc length and gas flow rate	Gas tungsten arc welding, L27 Box-Behnken experimental design, TLBO algorithm	Penetration, width of the weld	Welding current was the most dominant process parameter. An increase in welding current increases penetration and width of the weld and decreases with an increase in welding speed. The teaching learning-based optimization algorithm was effective
5	Nabavi et al. [13]	Weld bead characteristic	Laser edge welding process: HIS 1 316 L	Physical parameter & process parameter	AISI 316L	Geometry, mechanical and metallurgical aspects of weld bead	The developed approach is utilized to analyse a broad range of wild bead characteristics.
6	Khan et al. [26]	Laser beam defocusing on reprocess optimisation	22Mn B5 Grade press hardened steel/automated robotic laser welding	Open key mode & Close key mode	Numerical solution 3D finite element analysis, conical gauss in the volumetric heat source	The temperature field and weld pool geometry	The model can be used to predict the molten weld pool during geometry that stabilizes the liquid flow in the melt pool during high-speed laser welding
7	Huang et al. [27]	Optimisation of weld strength	Dissimilar joining of 304 stainless steel of PMMA	Nd:YAG pulsed laser, peak power, welding speed, defocus, pulse duration, frequency and Ar gas flow rate.	Taguchi design method	Welding parameters and joint quality	Optimized welding parameters and improved joint quality
8	Datta et al. [30]	Optimization of laser beam welding	Nitinol	Laser power, scan speed and focal position	Statistical regression analysis, grey wolf optimize cricket algorithm, desirability function analysis	Input-output relationship	Predicted results agree with the experimental results
9	Hietala et al. [28]	Optimisation of the tensile shear strength of laser-welded lap joints	Tensile shear strength of laser-welded lap joints	Electron backscatter diffraction	Finite element method	Shear response of weld pattern, stress analysis of longitudinal and transverse lap joints	A better comprehension of the response of difficult weld pattern, stress analysis of various longitudinal and transverse lap joint was made
10	Dong et al. [11]	Weld bead shape and temperature distribution	308 stainless steel and low carbon steel (St 37)	Welding speed, laser power nozzle distance, beam deviation	Fibre laser fusion welding	Weld bead field, temperature field	The effect of the nozzle distance on the temperature field was higher than that of the welding speed and laser power
11	Aravind et al. [25]	Optimisation of welding parameters	Ti6A14V alloys	Speed, power, flow rate, DOP, width and hardness	VIKOR, AHP	Weights of welding parameters	VIKOR method identified the 7th experimental run to contain optimised shielding gas flow rate parameter to obtain the weld with full depth of penetration
12	Horvath et al. [12]	Bead geometry modelling	Uneven base metal surface	Bead area, width, contact angles	Fuzzy system	Coefficient of the profile function	The model estimates the bead shape and outperforms the regression model
13	Kannan et al. [29]	Optimisation of laser welding process parameters	Nitinol shape memory alloy	Bead width, depth punctuation, microhardness, corrosion current destiny	Deng's similarly based approach, Yb:YAG laser welding	Weights of the output parameters, optimized weight parameters	The entropy weight method yielded more importance to microhardness. Deng's similarity approach run as the optimized parameter combination to obtain weld with full penetration, laser bead width, higher microhardness and corrosion resistance
14	Lei et al. [31]	Weld geometry prediction	Molten pool	Waist width (ww) & weld back (BW)	Genetic algorithm	Optimized initialized weight	The proposed model can effectively and steadily predict the geometric features of the weld
15	Sampreet et al. [32]	Nd:YAG laser welding	Ti-6AI-4V (Grade 5) alloy	Thickness using Nd: YAG laser welding	TOPSIS, ANOVA	Optimized parameters	Laser power had considerable control over the overall multi-objective function.

Table 1 Review of related literature to the study

S/N	Author and year	Domain of study	Work materials	Key parameters	Adopted method	Output (response(s))	Result(s)
16	Yang et al. [33]	Laser welding	-	Low fidelity & high fidelity	NSGA algorithm	Optimal solutions	The integrated optimal method could generate a desirable bead profile and reduce distortion in deep penetration laser welding
17	Reisgen et al. [34]	Laser welding	DP600 and TRIP 700 steel sheets	Power, speed, focus position	Response surface methodology (Box–Behnken design)	Weld quality, productivity and total operation cost	Strong, efficient and low-cost wild joints could be achieved using the optimum welding condition
18	Zhang et al. [35]	Laser pulse shaping	Pulsed Laser	CLBW continuous laser beam welding PLBW (Pulsed laser beam welding)	PLBW	Pulsed laser shapes	It predicts the sensitivity of solidification cracks, the formation and growth processes of hot cracks in pulsed laser welding
19	Qu et al. [36]	Weld geometry	Buried pipeline	Bevel angle, residual wild height, weld root opening and thickness	Numerical method and range analysis method	Weld geometry parameters	Deformation of explosion front surface is larger than that of explosion back surface of the buried pipeline
20	Paranthaman et al. [37]	CO_2 welding process	The dissimilar metal joint between stainless steel and corten steel	2mm thick steel sheets of DSS-2205 and Corten-steel	Duplex stainless steel (ASTM 332205 1332201)	Weld joint quality	To find out the optimum welding for a meters for welding dissimilar metal joint
21	Grünenwald et al. [38]	Weld geometry	Oscillation of the laser beam	Laser power, welding speed, and focal point	The laser beam (Oscillation)	Geometrical dimension of the weld	Lower oscillation frequencies with higher amplitudes were obtained
22	Prieto et al. [39]	E-mobility sector (battery coolers and battery boxes)	3003 aluminium alloy plates	Laser beam intensity profiles, oscillation frequencies	Overlap welding, CIVAN proprietary coherent beam combining and optical phased array technologies	Weld seam geometry width and depth of penetration	Defect-free weld seam geometry width and depth of penetration were obtained
23	Guo et al. [40]	Laser welding of stiffened plates	Al-Li alloy stiffened plates	Ultimate strength, failure mode, strain evolution, weld morphology	Tension experiments, digital image correlation, metallographic experiment	Welding deformation, residual stress	The finite element model can accurately predict the failure modes and ultimate strength of the stiffened plate
24	Gupta et al. [41]	Laser welding	Nb-1%C laser welding	Laser power, welding speed, beam diameter	Energy dispersive spectroscopy & X-ray diffraction phase analysis	Reduction of tensile strength and ductility of the joints	Laser welding is an alternative technique for the fabrication of reactive niobium alloy
25	Robertson and Kaplan [42]	Laser welding	Multibeam laser welding	Powder ratios high speed, films, time and location	Beam orientation	Impact of a molten front	Logging inter-key-hole wall of a beam process was impacted by the presence of a fully molten front
26	Mashinini and Hattingh [43]	Heat input and fatigue performance	Welded T6A14V sheet	Laser power and welding travel speed	Fatigue data	Weld geometry changes	Laser powder variation was not the sole determinant in fatigue life
27	Errico et al. [44]	Laser welding	AISI 304 stainless steel plate with AISi316 powder	Laser power, translation speed, power feed rate, gas flow rate and laser spot diameter	Coaxial powder feeding method	Evaluated filler powder in the welding	Demonstrated the feasibility of the laser welding of AISI 304 stainless steel with AISI 316L powder.
28	Liu et al. [45]	CO_2 laser-MAG hybrid welding process	Co_2 laser metal active gas (MAG) hybrid welding technique.	Wavelength	LD pump laser	Interference from the welding arc	A computer-based system is developed to collect the waveforms of the electrical welding
29	Sathish et al. [46]	4-GTAW welding	DMR 249 steel	DOP (depth of penetration)	RSM, Taguchi optimisation technique	Predict the RSM error	Optimized welding process parameters for achieving maximum DOP with better achieves during 4-GTAn Process
30	Chen et al. [47]	Laser MIG welding	Hybrid laser-MIG welding of aluminium alloy	Electromagnetic force, surface tension and buoyancy	Mathematical model	Calculated element distribution	Provides an effective method for parametric optimization to improve the properties of hybrid laser–MIG welding joints

Table 1 Review of related literature to the study (continue)

3. Methods

Based on the literature review, the study concerning laser welding on the optimisation of weld bead geometry has been extensively documented and noted to be adequate. However, the selection of parameters is an additional task to be conducted which considering the optimisation or even in its absence. For a deep insight into the problem studied, the physical representation of the weld bead geometry is considered. Fig. 1 shows the profile of a weld bead geometry accompanied by its parameters, namely, depth of penetration (D_p), bead weight (W_b), electrode deposit area (A_{ed}), the height of reinforcement (H_f), plate fusion area (A_{pf}) and wetting angle (τ) [7],[53]. Kurtulmus et al. [7] argued that measurement of weld bead parameters is the best achieved from their images. However, the weld bead geometry may be directly predicted from the measurements of welding process parameters such as the laser per, welding speed and feed speed for laser welding considerations.

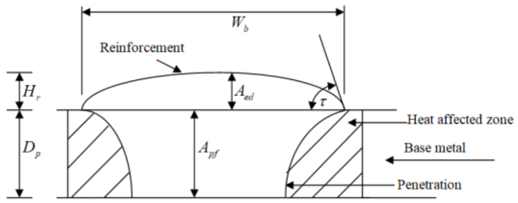

Fig. 1 Geometric parameters of a bead on plate weld [7], [53]; Key: A_{ed}: Electrode deposit area; A_{pf}: Plate fusion area; D_p: Penetration depth; H_r: Reinforcement height; W_b: Bead width; τ : Wetting angle

With the background of the weld bead geometry, the procedures taken in the present study are highlighted. The steps taken in this section are as follows:

Step 1 Extract the experimental data from Yang et al. [8], Table 2 in the present work.

Factors	Parameters	Level 1	Level 2	Level 3
A	Laser power, kW	2.4	2.6	2.8
B	Welding speed, m/min	1.5	2.1	3
C	Wire feed speed, m/min	2	5	8

Table 2 Process parameters and their Levels [8]

In this article, the three critical parameters that have been considered central to the evaluation of the weld bead geometrical analysis for the Al-Mg-Mn-Zr-Er alloy are laser power, welding speed and wire feed speed. These have been chosen according to the literature guidance and the experience of the authors. By some explanations of what these factors means are essential to understand the procedure proposed in the present work. First, the laser power is explained. The laser power, characteristically calculated in megawatts, accounts for the quantity of optimal power that the laser outputs [8, 54]. The laser power is central to the stability of the welding operation as it influences the weed bead geometry by regulating the quantity of energy absorbed into the Al-Mg-Mn-Zr-Er alloy. As described by Kant et al. [55], laser power is highly influential on process parameters. In a laser sheet bending process, they illustrated how the control aspect of the laser power works. They asserted that growth in the bend angle is experienced as growth in laser power is instituted. However, they cautioned that as it attains a peak, decay in performance is expected with additional growth in laser power.

The welding speed also referred to as travel speed, is the proportion of the length of weld to the time to weld. It may be viewed as the linear rate that the laser beam travels along with the Al-Mg-Mn-Zr-Er alloy and it is often expressed in millimetres per minute [8]. Furthermore, it is known in the literature that generally, the penetration made by the laser beam into the base material increases with the increase in the welding speed. Also, it decreases as the welding speed decreases [8]. The last factor, wire feed speed, which is often independent of the power setting. There are different positions to set the wire feed rate: off, good, too fast, too slow, far too first and far too slow. Matys et al. [54] suggested the inclusion of the following beam profile (Gaussian or flat top), size of the tip, tip angulation, energy and power of the laser, time of irradiation distance to the target and pulse duration and repletion rate.

Step 2 Deploy the analytical hierarchy process method to approximate weights of the various laser welding process parameters (Figure 2) [56].

Step 3 Introduce the fuzzy-analytical hierarchy process to approximate weights of the various laser welding process parameters (Figure 2) [57].

Step 4 Employ the best worst method to approximate weights of the various laser welding process parameters [58, 59].

Step 5 Use the entropy method to approximate the weights of the various laser welding process parameters [60, 61].

Step 6 Deploy the criteria importance through the inter-criteria correlation method to approximate weights of the various laser welding process parameters [62].

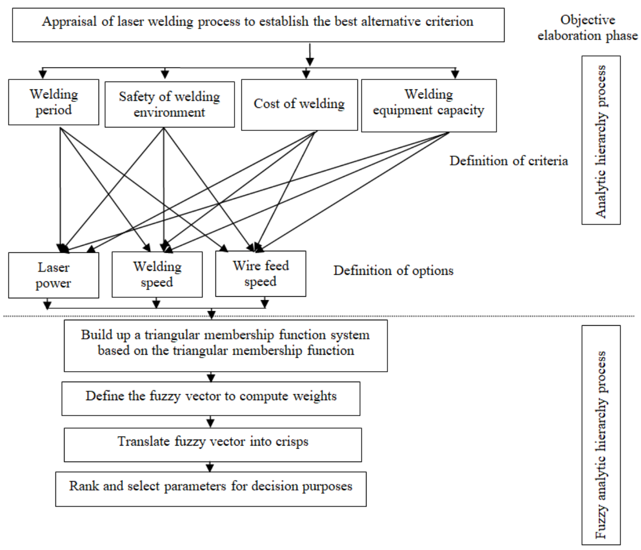

Fig. 2 AHP and FAHP aspects of laser welding for the CFPR problem (Odusoro and Oke, 2021a,b)

3.1 Analytical Hierarchy Process (AHP) Method

In this article, the analytic hierarchy process (AHP) is applied as a technique in the laser welding process to assist in arranging and examining the complicated welding process that consists of several important aspects that dictate the main output of the system. These aspects relate to the weld bead, penetration of the welding process on the work material. Out of these aspects, the analytic hierarchy process compels the researcher and decision-maker to select a goal such as the selection of welding parameters that promotes the optimisation of the weld bead characteristics in achieving a structured process, an inbuilt process in the AHP system is stimulated such that the criteria and the alternatives are related to the total goal of the system, which is identified as the optimisation of the weld bead geometry while selecting the best parameters that achieves this goal. The AHP has a history of being used successfully for prioritisation in several tasks within and outside the welding engineering domain. The AHP permits the establishment of a strategic goal in the welding process, which is fine-tuned as a group of weighted criteria that permits the researcher to score the prioritisation task through the aggregation of the expert’s opinions. In AHP, the subjective evaluations of the assessors are structured into a comparative importance scheme through Saaty's comparative matrix. The structure of the AHP is such that the goal of the laser welding process may be specified at the top level while the group of options is spelt out at the lowest level in the hierarchy of analysis. Within the two extremes of the top-level goal and the lowest level, two sets of criteria, the general one and the sub-criteria are defined. The process of judgement is based on a nine-point scale of integers running from 1 to 9 while the complementary values are also represented.

The following steps are undertaken in the use of the AHP [56]:

Step 1 A pair-wise comparison matrix is developed using the scale of relative importance

A matrix is a framework containing information about the laser welding criteria of laser power, welding speed and welding rate speed arrange both in columns and rows with each criterion established in a single row or column where the intersection is often ignored. The matrix is often in a square matrix that permits a pairwise comparison of the possible groupings of criteria. Pairwise comparison is a procedure conducted to compare laser welding factors in pairs to ascertain if a factor is preferred to the other. The number of pairwise comparisons possible is a function of the number of factors in the square matrix. The higher the number of factors, the greater the number of pairwise comparison entries and vice-versa.

Step 2 Each column on the pair-wise comparison matrix table is then summed up

Step 3 Each segment on the pair-wise comparison matrix table is then divided by the total sum on its corresponding row.

Step 4 The criteria weights are calculated using Equation (1) [56]:

Criterion weight (CW) =
Sum of values on rows/total number of factors (1)

Notice that the total number of factors is 3

Step 5 To check for consistency of the obtained results, the weighted sum (WS) is first off calculated by multiplying each factor/criterion by their corresponding criteria weight and then summing up each row.

Step 6 The ratio of the weighted sum to criteria weight (WS/CW) is calculated for each factor.

Step 7 The consistency index (*CI*) is calculated using Equation (2) [56]:

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad (2)$$

where $\lambda_{\max}$ is the largest eigenvalue of the n-order matrix and is the average of the ratio of the weighted sum to criteria weight, *n* is the number of criteria/factors, which is 3

Step 8 The consistency ratio (*CR*) is then calculated using Equation (3) [56]:

CR = CI/Random index (RI) (3)

; where the random index is the consistency index of the randomly generated pair-wise matrix.

The consistency ratio is the proportion of the consistency index to the random index. It is an indicator of the comparative strength of the analysis conducted using the expert's opinion. In this case, one of the authors was the assessor and the senior author verified the assessment for completeness and correctness. As the consistency ratio decreases, the better the degree of satisfaction of the researcher with the assessment conducted. However, an increase in the value of the consistency ratio beyond 0.1 indicates poor data and adjustments need to be undertaken to ascertain that the consistency ratio falls within limits. The consistency ratio is used to decide if the assessor could proceed with the results of the ranking and select the best candidate or not. According to Saaty [56], as the consistency ratio is above 0.1 the obtained rankings and choice of the best to the worst criterion is not consistent and unreliable. Interestingly, if a value of 0 is obtained, a perfectly consistent evaluation of the ranks for the criteria is made. The evaluations in this instance are reliable and decisions made on them are promising.

The role of consistency ratio for the weight calculations involving the laser welding of the Al-Mg-Mn-Zr-Er alloy is to evaluate the degree to which the method predicts the attributes of the factors for the Al-Mg-Mn-Zr-Er alloy. Consistency occurs when the ratio obtained is less than 0.10, indicating a strong association between the method and the attributes of the data. For instance, a value of 0.05 shows a promising consistency in the evaluation. An analysis of consistency is essential since significant benefits of the method are obtained from the understanding that the quality of data, particularly those obtained from experts' judgments assists in revealing the competence of the method to correctly predict the best to the worst criteria according to the aim of applying the analytic hierarchy process.

3.2 Fuzzy Analytical Hierarchy Process (FAHP) Method

The fuzzy analytic hierarchy process (FAHP) is a modification of the AHP that corrects the weakness of the AHP regarding its inability to track the imprecision and uncertainty inherent in the evaluation of the laser welding process parameters. While coordinating the measures from the field the decision-maker might have introduced errors and also errors do arise from other sources too. These errors are corrected by using the FAHP method, which combines the AHP method and the fuzzy logic method. Consequently, the FAHP draws inspiration from the AHP method by following the Saaty's importance scale but with modifications to account for values in-between those being considered. Thus, fuzzy numbers are created uniquely different from others as it possesses three component values of a lower component, a middle component and a higher component whose value representations are progressive. To achieve the goal of FAHP, two common scales are used to achieve priority, namely the triangular and trapezoidal scales. However other methods of scales have been developed but not common.

The steps taken in the fuzzy analytical hierarchy process approach are as follows:

Step 1 The scale of relative importance as used in the analytical hierarchy process method is changed to a fuzzy scale of relative importance which uses fuzzy numbers.

Step 2 A pair-wise comparison matrix is developed using the scale of relative importance

Step 3 The pair-wise comparison matrix obtained will be changed to fuzzy numbers using the fuzzy scale of relative importance. To change the values of fractions, (4) is used [57]:

$$\tilde{A}^{-1} = (l,m,u)^{-1} = \left(\frac{1}{l},\frac{1}{m},\frac{1}{u}\right) \tag{4}$$

Step 4 The fuzzy geometric mean $\tilde{r}_i$ is calculated and is the cube root of the multiplication of each value in each column, (5) [57]:

$$\tilde{A}_1 \times \tilde{A}_2 = (l_1,m_1,u_1)\times(l_2,m_2,u_2)$$
$$= (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2) \tag{5}$$

Step 5 The fuzzy weights $\tilde{w}_i$ are calculated [57]:

$$\tilde{w}_i = \tilde{r}_i \times (\tilde{r}_1 + \tilde{r}_2 + \tilde{r}_3)^{-1} \tag{6}$$

Step 6 The fuzzy weights will then be changed to numerical values, (7) [57]:

$$w_i = \frac{l+m+u}{3} \tag{7}$$

3.3 Best Worst Method

Although there are numerous effective multicriteria methods, the development of novel methods that are straightforward always attracts the interest of decision-makers and researchers. The best-worst method is a novel method that emerged in 2015 with unique descriptions of two features that are uncommonly emphasized in other methods [58, 59]. These are the least and most essential criteria that are identified by the experts. Then the assessor establishes the levels, that the other criteria are better than the considered criteria; the assessor also determines the level at which the considered criterion is better than the worst criterion [58],[59].

In this method, the most important criteria (wire feed speed) and the least important criteria (laser power) are used to create a linear programming problem and the Excel 16 software was used for this computation. Three decision criteria are selected in the software and the most and least important criteria are also noticed. The preference of the decision-maker is then expressed on 'the best criterion over all the other criterion', and the preference of 'all the other criteria over the worst' by selecting a number between 1 and 9 as was the same case in the AHP method where the scale of relative importance was used for this decision. The best worst method follows the following steps [58], [59]:

Step 1 Establish the set of decision criteria.

Step 2 Establish the preference of the best criterion over others by employing a scale of comparative importance which ranges from 1 to 9.

Step 3 Determine the preference of the worst criterion over all the other criteria, using a scale of relative importance from 1 to 9.

Step 4 Find the optimal weight using (8)-(12) [58],[59]:

$$Min \xi_i \tag{8}$$

Subject to

$$\left| w_b - a_{Bj} w_j \right| \le \xi_i \text{, for all } j \tag{9}$$

$$\left| w_j - a_{jw} w_w \right| \le \xi_i \text{, for all } j \tag{10}$$

$$\sum w_j = 1 \tag{11}$$

$$w_j \ge 0 \text{, for all } j \tag{12}$$

; where ε_l is the term for the objective function,

w_{lp}, w_s and w_{wfs}, are the weights of laser power, welding speed and wire feed speed respectively

a_{Bj} is the value in the columns considering the row parameter one at a time

w_j is the value of the individual criterion when a particular factor is considered

It may also be computed by using the BWM excel solver.

3.4 Entropy Method

The entropy weight approach is claimed to be an objective approach as it excludes inputs from experts in the area of laser welding and only acts on a set of weight conversion mechanisms [21],[60],[61],[63]. Consequently, it has a huge popular usage by decision-makers in the engineering field. The entropy is based on the degree of disparity among the criteria where the higher degree of dispersion indicates more level of differentiation among the criteria and more information may be obtained from the association of the criteria by deploying the entropy method.

The steps taken in this method are as follows [21],[60],[61],[63]:

Step 1 The Decision matrix (extracted data) is normalized using Equation (13) [21, 60, 61, 63]:

$$r_{ij} = \frac{x_{ij}}{\sum_{j=1}^{m} x_{ij}} \quad (13)$$

where r_{ij} is the normalized matrix and x_{ij} is the individual value in each segment

Step 2 The entropy, e_j is calculated using Equation (14) [21, 60, 61, 63]:

$$e_j = -h\sum_{i=1}^{m} r_{ij} \ln r_{ij} \quad (14)$$

; where $h = \frac{1}{\ln m}$

e_j is the entropy for the j^{th} assessment parameter within the boundary of the assessment parameters [61]

m is the number of alternatives, which is 3 [21], [60],[61],[63].

Step 3 The degree of diversification, d_j is calculated using Equation (15) [21], [60], [61], [63]:

$$d_j = 1 - e_j \quad (15)$$

Step 4 The weight of each criterion is then calculated, Equation (16) [21, 60, 61, 63]:

$$w_j = \frac{d_j}{\sum d_j} \quad (16)$$

3.5 Criteria Importance through Inter-Criteria Correlation (CRITIC) Method

The birth of the unique method, CRITIC was in 1995, which could be applied to achieve an understanding of the characteristics weights of the elements of the decision matrix, notably the laser welding parameters of laser power, welding speed and the wire feed speed. The CRITIC method has different phases of detailing the weight and the ranking attributes. It employs the coefficient of correlation among the various characteristics to establish the association among the mentioned parameters.

The steps taken in this method are as follows:

Step 1 The decision matrix is normalized using Equation (18) [62]:

$$\overline{X}_{ij} = \frac{X_{ij} - X_j^{worst}}{X_j^{best} - X_j^{worst}} \quad (17)$$

Step 2 The standard deviation, σ_j of each column, is estimated and is done with the aid of the excel software.

Step 3 The symmetric matrix of n x n with element r_{jk} is determined and is the linear correlation coefficient between the vectors x_j and x_k and this is also done using the Excel 16 software.

Step 4 Calculate the measure of the conflict created by criterion j concerning the decision situation defined by the rest of the criteria using the following expression:

$$\sum_{k=1}^{m}(1 - r_{jk}) \quad (18)$$

Step 5 The quantity of the data about each criterion is then determined using Equation (19) [62]:

$$C_j = \sigma_j \times \sum_{k=1}^{m}(1 - r_{ij}) \quad (19)$$

Step 6 The objective weights are finally calculated using Equation (20) [62]:

$$w_j = \frac{C_j}{\sum_{k=1}^{m} C_j} \quad (20)$$

However, the consistency index, CI, of the result is then calculated using Equation (21) [56]:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (21)$$

But, the consistency ratio (CR) is given by Equation (22) [56]:

$$CR = CI/RI \quad (22)$$

; where RI is the random index

Besides, the best worst method has been distinguished as less computationally laborious regarding the computational time to achieve data collection, calculation and analysis compared with the analytic hierarchy process (AHP) method. But the AHP method has outstanding benefits, including the ability to incorporate a wide range of criteria, extensive usage in engineering practice, it is trusted by many researchers. The CRITIC method is preferred to users because of its objectivity in assessment and considers the contrast intensity as well as the conflicting feature of the assessment criteria. For the entropy method, it has much attraction because users it has objectivity in-built in it. It has been stated to have wide applications. The fuzzy AHP is credited for transforming qualitative descriptions into quantitative interpretation with uncertainty and imprecision content.

3.6 Comparison Indices

In attempts to compare a few significant multicriteria characteristics, two principal comparative indices, arithmetic mean (Equation (23)) and root mean square (Equation (24)) were built up. The results of the application are discussed in the next section.

$$A = \frac{1}{n}\sum_{i=1}^{n}(L_p + W_s + W_{fs}) \tag{23}$$

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(L_p + W_s + W_{fs})} \tag{24}$$

; where RMS is the root mean square, n is the number of measurements such as laser power (l_p), welding speed (w_s) and wire feed speed (w_{fs}) and A is the arithmetic mean.

4. Results and Discussion

4.1 Analytical Hierarchy Process Method

A pair-wise comparison matrix is created which gives the relative importance of various attributes concerning the goal or objective. It compares two of the attributes at a time and shows their relative importance. It is created with the help of a scale of relative importance which is as follows:

The scale of relative importance

1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance
2,4,6,8	Intermediate values
1/3, 1/5, 1/7, 1/9	Values for Inverse Comparison

To solve the pair-wise comparison matrix, a 3 x 3 matrix will be provided as there are three criteria: Laser power, welding speed, and wire feed speed. Before going further, it is important to note that while making decisions, the decision-maker has to select the most important factor and also the least important factor and this is normally due to preference. Concerning these three factors, wire feed speed has been chosen to be the most important while laser power has been chosen to be the least important, which means that mathematically, wire feed speed > welding speed > laser power.

Factors	Laser power	Welding speed	Wire feed speed
Laser power	1	$x/3x = 1/3$	$x/7x = 1/7$
Welding speed	$3x/x = 3$	1	$x/5x = 1/5$
Wire feed speed	$7x/x = 7$	$5x/x = 5$	1

Table 3 Pair-wise comparison matrix

Pairwise comparison in laser welding is adopted from L.L. Thurstone's law of comparative judgment. This principle empowers the researcher (expert in the present case) to compare the factors of the laser welding process in pairs and judge which factor is preferred to the other using number assignments. Table 3 shows the results of the pairwise comparison undertaken among the three laser welding factors of laser power, welding speed and wire feed speed. The explanation of the table proceeds from the second row containing the factor, laser power and its interaction with itself, welding speed and wire feed speed. Matched against itself, the laser power means that laser power is as important as itself and therefore given 1 point. Likewise, all entries of the factor matched against itself obtain a value of 1. Still along the second row but at the intersection of the laser power with the welding speed, a judgment of 1/3 is eventually obtained. To understand the computation, the symbol x is attached as the maximum possible score between the laser power and any other factor, but the welding speed is evaluated by the researcher as not as important as the laser power. This means the welding speed carries the third weight of importance as the laser power. This is why a value of $x/3x$ is assigned to this cell and the outcome is 1/3. Similarly, the wire feeds speed is judged to be not as important as the laser power. It is to the strength of one-seventh in importance and therefore assigned a value of $x/7x$ and 1/7. The reverse of these values of 3 and 7 is given to the intersection of welding speed with laser power (row 3) and wire feed speed with laser power (row 4), respectively. Thus, by using the same idea, Table 2 is completed. The sum of each column is then calculated and is shown in Table 4. Each value on each segment is then divided by the sum on each column, Table 5. The criteria weights are therefore estimated by summing the rows by the total and dividing by the total number of factors, which is equal to 3, Table 6.

Factors	Laser power	Welding speed	Wire feed speed
Laser power	1	0.33	0.14
Welding speed	3.00	1	0.20
Wire feed speed	7.00	5.00	1
Total	11.00	6.33	1.34

Table 4 Sum of pair-wise comparison matrix

Factors	Laser power	Welding speed	Wire feed speed
Laser power	0.0909	0.0526	0.1045
Welding speed	0.2727	0.1579	0.1493
Wire feed speed	0.6364	0.7895	0.7463

Table 5 Pair-wise comparison matrix

Factors	Laser power	Welding speed	Wire feed Speed	Sum of weights	CW
Laser power	0.0909	0.0526	0.1045	0.2480	0.083
Welding speed	0.2727	0.1579	0.1493	0.5799	0.193
Wire feed speed	0.6364	0.7895	0.7463	2.1721	0.724

Table 6 Criteria weights of the AHP Method

Table 6 should be the weights for the considered factors but while dealing with the AHP method, the consistency of the result should be calculated. This is done first, by calculating the ratio of the weighted sum to criteria weights. The weighted sum is calculated by multiplying each element by their criteria weight and adding the row values as shown in Table 7. The ratio of the weighted sum to criteria weight is then calculated (WS/CW), Table 8.

Criterion weight (CW)	0.083	0.193	0.724	
Factors	Laser power	Welding speed	Wire feed speed	*WS*
Laser power	0.0075	0.0102	0.0756	0.0933
Welding speed	0.0226	0.0305	0.1081	0.1611
Wire feed speed	0.0526	0.1526	0.5403	0.7455

Table 7 The weighted sum on the AHP method

Factors	WS/CW
Laser power	1.1286
Welding speed	0.8336
Wire feed speed	1.0297

Table 8 The ratio of the weighted sum to criteria weight of the AHP method

The consistency index, CI, of the result is then calculated using (21); where

$$\lambda_{\max} = \frac{1.1286 + 0.8336 + 1.0296}{3} = 0.9973$$

Therefore, *CI* = (0.9973-3)/(3-1) = -0.6676

The consistency ratio of the result is finally calculated from Equation (22). The random index is the consistency index of the randomly generated pair-wise matrix, which is given in Table 9 obtained from the literature (for up to 10 criteria).

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 9 Random index for *n* =10 criteria

Therefore, for three criteria:

CR = -0.6676/0.58 = -1.1510

For consistency, CR < 0.10, which is satisfied in this case as the obtained CR is -1.1510. The calculated weighted result is therefore consistent. In summary, the weights obtained from the AHP method are given in Table 10.

Laser power	0.083
Welding speed	0.193
Wire Feed speed	0.724

Table 10 AHP weights for criteria

4.2 Analysis of Fuzzy Analytical Hierarchy Process Method

To apply the FAHP to evaluate the weights of the laser welding parameters, the scale of importance adopted for the AHP is transformed into a fuzzy scale where the crisp numeric values, which are individual are represented by fuzzy numbers, each of which comprises three components identified as the lower, middle and upper values, which are the first, second and third components, respectively of the fuzzy numbers. These three component representation is unique for the triangular fuzzy numbers adopted in the present study. While other component types abound such as the trapezoidal, for convenience of computations and are commonly used, the triangular fuzzy numbers are adopted in the present article. With an equal number of descriptions as the AHP such as equal, moderate, strong, very strong, extremely strong and intermediate values, the FAHP differs in the scale of importance specification by having three components of each fuzzy number. For instance, the "equal" description has the fuzzy number as "(1, 1, 1)", which means the lower, middle and upper components of the fuzzy number are 1. Similarly, other fuzzy numbers representing moderate, strong, very strong, extremely strong and intermediate values are respectively stated as (2, 3, 4), (4 5 6), (7, 8, 9), (9, 9, 9), (1, 2, 3), (3, 4, 5), (5, 6, 7) and (7, 8, 9). However, the advantage of using the fuzzy scale of comparative importance is to solve the limitation of the ordinary scale of comparative importance that does not tackle the values in-between the various criteria such as 2.5, 3.5, etc.

The fuzzy scale of relative importance

Equal	(1,1,1)
Moderate	(2,3,4)
Strong	(4,5,6)
Very Strong	(6,7,8)
Extremely Strong	(9,9,9)
Intermediate values	(1,2,3)
Intermediate values	(3,4,5)
Intermediate values	(5,6,7)
Intermediate values	(7,8,9)

The fuzzy scale of relative importance solves the limitations of the ordinary scale of relative importance which does not account for values in between the different criteria. For example, values like 2.5,3.5, etc. Table 2 is recalled for the computation here. The values are then changed to their corresponding fuzzy numbers, Table 11.

The next step is to calculate the fuzzy geometric mean, $\tilde{r}_i$ which was proposed by Buckley (1985) as reported in Okponyia and Oke [57], Table 12. The fuzzy weights are then calculated using (6):

$$\tilde{w}_i = \tilde{r}_i \times (r_1 + r_2 + r_3)^{-1}$$

; where $r_1 + r_2 + r_3$ = (3.8929,4.477,5.071), therefore:

$$(r_1 + r_2 + r_3)^{-1} = \left(\frac{1}{5.071}, \frac{1}{4.477}, \frac{1}{3.8929}\right) \text{(Table 13)}$$

Factors	Laser power	Welding speed	Wire feed speed
Laser power	(1,1,1)	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	$\left(\frac{1}{8},\frac{1}{7},\frac{1}{6}\right)$
Welding speed	(2,3,4)	(1,1,1)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
Wire feed speed	(6,7,8)	(4,5,6)	(1,1,1)

Table 11 Transformation of pair-wise comparison matrix to fuzzy numbers

Factors	Laser power	Welding speed	Wire feed speed	$\widetilde{r}_i$
Laser power	(1,1,1)	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	$\left(\frac{1}{8},\frac{1}{7},\frac{1}{6}\right)$	(0.315, 0.3625, 0.4368)
Welding speed	(2,3,4)	(1,1,1)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$	(0.6934, 0.8434, 1)
Wire feed speed	(6,7,8)	(4,5,6)	(1,1,1)	(2.8845, 3.2711, 3.6342)

Table 12 The geometric mean of the FAHP method

$\widetilde{r}_i$	$\widetilde{w}_i$
(0.315, 0.3625, 0.4368)	(0.0621, 0.081, 0.1122)
(0.6934, 0.8434, 1)	(0.1367, 0.1884, 0.2569)
(2.8845, 3.2711, 3.6342)	(0.5688, 0.7306, 0.9335)

Table 13 Fuzzy weights $\widetilde{W}_i$

Defuzzification aims at converting the fuzzy weights into crips numeric values. Consequently, the adopted approach is the centre of the area, which is commonly established for computing weight. This is employed as $w_i = (l + m + u)/3$ where the l is the first and the lower value of the three components that represent the fuzzy number (0.0621, 0.081, 0.1122), which is 0.0621. The symbol is the middle term of the components, which is 0.081, while w is the upper and last value in the components representing the fuzzy numbers, which is 0.1122. These three values are averaged to become 0.0851, which is placed in front of the fuzzy number (0.0621, 0.081, 0.1122) as the representative crisp numeric value. Similar computations are made to obtain the crisp numeric values for (0.1367, 0.1884, 0.2569) as 0.194 while (0.5688, 0.7306, 0.9335) yields 07443. To aid further computation, these three numeric values are added as 1.0234. However, as the total value exceeds 1, it becomes unacceptable as the standard practice is to have a total value of 1. In such a case, the normalization of the individual crisp numeric value is pursued such that the scale of measurement is 1. This is obtained by dividing the value obtained from the defuzzification for each parameter by the total of all the defuzzified values. As an instance, the defuzzified value of the laser power is 0.0851 is divided by 1.0234, a value of 0.083 is obtained, which is then a normalized value for the laser power. This means that while attaching importance to weights and apportioning resources to the parameters, the proportion allocated to the laser power is 8.3%. Consequently, similar computations are taken and weights of 0.19 and 0.727 are obtained for the welding speed and wine feed speed, respectively, representing 195 and 72.7% correspondingly. Thus, by implementing the FAHP method, the suggestion is to consider the wine feed speed having 0.727 weight as the first position welding speed with a weight of 0.19 as the second position and laser power with the weight of 0.083 as the third position (Table 14). These values already account for uncertainty and imprecision. It means that the computation using the FAHP takes into consideration all activities that may bring imprecision into the evaluation such as the errors in the measuring laser welding equipment or those introduced by the process engineer during readings. However, these errors were not accounted for by the results of the AHP, which yields to same as the laser power of 0.083, welding speed of 0.193 and the wine feed rate of 0.724. But these two sets of values are the same in AHP and FAHP, which implies that very negligible imprecision and uncertainty, have been introduced into the measurements and can be overlooked.

$\widetilde{w}_i$	Weight, w_i
(0.0621, 0.081, 0.1122)	0.0851
(0.1367, 0.1884, 0.2569)	0.194
(0.5688, 0.7306, 0.9335)	0.7443
Total	1.0234

Table 14 Defuzzied weights

Factors	w_i	Normalized weights
Laser power	0.0851	0.0851/1.0234=0.083
Welding speed	0.194	0.194/1.0234=0.19
Wire Feed speed	0.7443	0.7443/1.0234=0.727
Total	1.0234	1.000

Table 15 Normalized weights for the FAHP method

The sum of the numerical weights equals 1.0234 which is not accepted. The accepted value is 1. These weights, therefore, have to be normalized, Table 15. Data from Table 15 containing the normalised FAHP was compared with the literature data from Okponyia and Oke [57], which analysed the electrical discharge machining process parameters of peak current, pulse on time and duty factor. The obtained values for these correspondingly mentioned values are 0.1051, 0.2290 and 0.6658. However, on running the correlation index on the association between the two set of data, a high correlation coefficient of 0.9984 was obtained, indicating a strong association between the two data sets, which suggests the usefulness of the FAHP method to solve the problem.

4.3 Analysis of Best Worst Method

The results obtained from this method are shown in Tables 16 and 17. Figure 1 also shows the plot given by the MS Excel solver.

Criteria number = 3	Criterion 1	Criterion 2	Criterion 3
Criterion name	Laser power	Welding speed	Wire-speed feed

Selected best parameter →	Wire-speed feed
Selected worst parameter →	Laser power

Best to others	Laser power	Welding speed	Wire-speed feed
Wire-speed feed	7	5	1

Others to the worst	Laser power
Laser power	1
Welding speed	3
Wire-speed feed	7

Weights	Laser power	Welding speed	Wire-speed feed
	0.091	0.169	0.740

Table 16 BWM MS Excel results

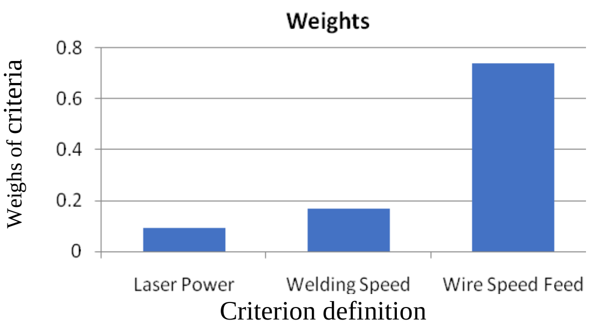

Fig. 2 BWM weights (provided by MS Excel software)

The best-worst method depends on the optimal weight with which a linear programming model could be formulated. The objective function of the linear programming model is min ε_l. In this case study, the weights of laser power, welding speed and wire feed speed are represented as w_{lp}, w_s and w_{wfs}, respectively. The a_{Bj} is noted as the coefficient of w_j. The a_{Bj} is the preference score of x criterion concerning each other criterion. So along the first row of laser power, the value of a_{Bj} will be 0.090, 0.0526 and 0.1064. Now there is a consideration to minimize the ε_l subject to the inequality constraints. The last equation $\sum w_j = 1$ means the sum of all the weights of w_{lp}, w_s and w_{wfs} will be 1. By checking through the first inequality constraint, w_b minus $a_{Bj}w_j$ should be less than or equal to ε_l. In this problem, w_b is the weight of the best criterion (wire speed feed) minus the a_{Bj} value, which should be less or equal to ε_l. Mathematically, the objective function is Min ε_l; subject to

$$w_{lp} \text{-} 0.0909\ w_{lp} \leq \varepsilon_l$$

$$w_{lp} \text{-} 0.0525\ w_s \leq \varepsilon_l$$

$$w_{lp} \text{-} 0.1064\ w_{wfs} \leq \varepsilon_l$$

It means that we have three inequality constrains for the three criteria. By considering the next inequality constraint where the w_j minus $a_{jw}w_w$ should be less than ε_l. Thus, for the least (worst) important criterion is laser power, we have

$$w_{lp} \text{-} 1w_{lp} \leq \varepsilon_l$$

$$w_{ws} \text{-} 3w_{lp} \leq \varepsilon_l$$

$$w_{wfp} \text{-} 7w_{lp} \leq \varepsilon_l$$

By merging the inequalities formulated from the best criterion and the worst criterion, the objective function is Min ε_l (25); subject to

$$w_{lp} \text{-} 0.0909\ w_{lp} \leq \varepsilon_l \tag{26}$$

$$w_{lp} \text{-} 0.0525\ w_s \leq \varepsilon_l \tag{27}$$

$$w_{lp} \text{-} 0.1064\ w_{wfs} \leq \varepsilon_l \tag{28}$$

$$w_{ws} \text{-} 3w_{lp} \leq \varepsilon_l \tag{29}$$

$$w_{wfp} \text{-} 7w_{lp} \leq \varepsilon_l \tag{30}$$

In the new formulation, the inequality (4) vanishes. But

$$w_{lp} + w_{ws} + w_{wfs} = 1 \tag{31}$$

; where $w_{lp,}\ w_{ws},\ w_{wfs} \geq 0$

This linear programming model needs to be solved, which yields

w_{lp} = 0.091

w_{ws} = 0.169

w_{wfs} = 0.740

Laser power	0.091
Welding speed	0.169
Wire feed speed	0.740

Table 17 BWM weights for criteria

4.4 Analysis of Entropy method

The results obtained from this method are shown in Tables 18 and 19.

Serial No.	Laser power	Welding speed	Wire feed speed
1	2.4	1.5	2
2	2.6	2.1	5
3	2.8	3	8
$\sum_{j=1}^{m} x_{ij}$	7.8	6.6	15

Table 18 Process of normalizing the decision matrix in the entropy method

Serial No.	Laser power	Welding speed	Wire feed speed
1	0.3077	0.2273	0.1333
2	0.3333	0.3182	0.3333
3	0.3590	0.4545	0.5333

Table 19 Normalized decision matrix for entropy method

The entropy of the data is then calculated where h = 1/ln(m) and m is the number of alternatives, which is three. Therefore, h = -0.910239227. However, by using the equation for h, Table 20 is obtained.

Serial No.	Laser power	Welding speed	Wire feed speed
1	-0.3627	-0.3367	-0.2687
2	-0.3662	-0.3644	-0.3662
3	-0.3678	-0.3584	-0.3353
$\sum_{i=1}^{m} r_{ij} \ln r_{ij}$	-1.0966	-1.0595	-0.9701
e_j	0.9982	0.9644	0.8830
$d_j = 1 - e_j$	0.0018	0.0356	0.1170

Table 20 Calculated entropy in entropy method

Summing the row d_j gives 0.0018 + 0.0356 + 0.1170 = 0.1544. Therefore, to get the weights of each criterion, Equation (17) is used and the results are shown in Table 21.

Laser power	0.012
Welding speed	0.231
Wire feed speed	0.758

Table 21 Entropy method weights for criteria

4.5 Analysis of Criteria Importance Through Inter-Criteria Correlation (CRITIC) Method

The results obtained from this method are shown in Tables 22 and 23.

Serial No.	Laser power	Welding speed	Wire feed speed
1	2.4	1.5	2
2	2.6	2.1	5
3	2.8	3	8
X_j^{best}	2.8	3	8
X_j^{worst}	2.4	1.5	2
$X_j^{best} - X_j^{worst}$	0.4	1.5	6

Table 22 Process of normalizing in CRITIC method

Serial No.	Laser power	Welding speed	Wire feed speed
1	0	0	0
2	0.5	0.4	0.5
3	1	1	1

Table 23 CRITIC method normalized matrix

The standard deviation, σ_j for each column, is then calculated using the Excel 16 software, Table 24. The next step taken is to determine the symmetric matrix of $n \times n$ with element r_{jk}, which is the linear correlation coefficient between the vectors x_j x_k and this is also done using the Excel 16 software, Table 25.

Serial No.	Laser power	Welding speed	Wire feed speed
1	0	0	0
2	0.5000	0.4000	0.5000
3	1.0000	1.0000	1.0000
σ_j	0.5000	0.5033	0.5000

Table 24 The standard deviation for the CRITIC method

Factor	Laser power	Welding speed	Wire feed speed
Laser power	1.0000	0.9934	1.0000
Welding speed	0.9934	1.0000	0.9934
Wire feed speed	1.0000	0.9934	1.0000

Table 25 Symmetric matrix of CRITIC method

Next, is to calculate the measure of the conflict created by criterion *j* concerning the decision situation defined by the rest of the criteria, Table 26. The quantity of the data about each criterion is then determined, Table 27.

Factor	Laser power	Welding speed	Wire feed speed	$\sum_{k=1}^{m}(1-r_{jk})$
Laser power	0	0.0066	0	0.0066
Welding speed	0.0066	0	0.0066	0.0132
Wire feed speed	0	0.0066	0	0.0066

Table 26 The measure of conflict in the CRITIC method

Factor	σ_j	$\sum_{k=1}^{m}(1-r_{jk})$	C_j	Objective weight
Laser power	0.500	0.0551	0.0275	0.243
Welding speed	0.5292	0.1102	0.0583	0.514
Wire feed speed	0.500	0.0551	0.0275	0.243
$\sum_{k=1}^{m}C_j$			0.1134	

Table 27 Quantity of data about each criterion and CRITIC method weights for criteria

The objective weights are finally calculated as shown in Table 27. In summary, using the five techniques for estimating weights, the result is given in Table 28. Table 28 is the summary of results from the analysis using the fire methods of multicriteria analysis namely, AHP, FAHP, BWM, entropy and CRITIC. The AHP produces the wire feed speed as the best candidate parameter with a weight value of 0.724 while the second position was allocated to the welding speed with 0.193 as the value of the weight. However, the third position was allocated to the laser power with a weight of 0.083. By considering three other weight determining methods analyzed, namely the FAHP, BWM and entropy, the pattern of performance by the candidate criteria was similar to the one observed for the AHP method. Thus, the wire feed speed maintained the first position in each of the FAHP, BWM and entropy methods with weights of 0.737, 0.740 and 0.758, respectively. The welding speed occupied the second position in all three methods with weights of 0.190, 0.169 and 0.231 for the FAHP, BWM and entropy, methods, respectively.

Method ⟶ Criterion ↓	AHP	FAHP	BWM	Entropy	CRITIC
Laser power	0.083	0.083	0.091	0.012	0.243
Welding speed	0.193	0.190	0.169	0.231	0.514
Wire feed speed	0.724	0.737	0.740	0.758	0.243

Table 28 Summary of weights of criteria for the five methods

The third position, allocated to the laser power, is also consistent in all the other three methods such as 0.083 for FAHP, 0.091 for BWM and 0.012 for entropy methods. However, there is a variation of the pattern of performance of the criteria when the CRITIC method was compared to the AHP, FAHP and entropy methods. Thus, in CRITIC methods, the first, position is allocated to the welding speed with the weight of 0.514, and a tie of position in the second context is given to both the laser power and wire feed speed with each weighing 0.243. Now, being given five approaches, there is a need to select the best recommendation for the management of the laser welding workshop. By considering uncertainty, only the FAHP considers uncertainty in its evaluation. But uncertainty is essential and should be regulated. Thus, the results of the FAHP method are recommended for implementation in the plant as it contains uncertainty elements that were regulated by the method.

In this section, the FAHP method was suggested as the best based on the fact that it corrects the results of the AHP method to reduce uncertainty and imprecision. However, perhaps an equally acceptable argument is to use quantitative indices to compare all the five methods and then judge on the outcomes. To attain this, the arithmetic means method (Equation (23)) and the root mean square (Equation (24)) were applied to the data in Table 28. The results from the application of the arithmetic mean method on the five methods places the FAHP method as the best with an arithmetic mean of 0.3367 while the entropy method obtained the second position with a value of 0.3337. Furthermore, the third position is allocated to the three methods of AHP, BWM and CRITIC with an arithmetic mean of 0.3333.

Besides, the results of the root mean square on the methods are slightly at variance with the two previous recommendations of the FAHP method as the first and best position. Surprisingly, the entropy method displaces the FAHP method to the second position by a 7.15% edge over the FAHP method. Thus, the entropy method was the first position with the root mean square (RMS) value of 0.2094 while the second to the last positions were allocated to FAHP (RMS, 0.1954), BMW (RMS, 0.1948), AHP (RMS, 0.1894) and CRITIC (RMS, 0.1274). Interestingly, with the additional information from the results of the arithmetic mean and the root means square, there are more recommendations on the choice of the FAHP method as the first position compared with the entropy method. Therefore, it is safe to conclude that the FAHP method is the best and recommended for implementation in the workshop.

5. Results and Discussion

In this article, the prioritization of laser welding parameters including laser power, welding speed and wire feed speed using the Al-Mg-Mn-Zr-Er alloy sheets, was conducted. Five important multicriteria methods were adopted to achieve the goal and these are the AHP, FAHP, entropy, CRITIC and the best-worst method. Consequently, the analysis revealed that the wire speed feed is the leading parameter, followed by the welding speed and the last parameter in ranking is the laser power. Moreover, the current results in one method have been validated by the other four methods. This research equips the workshop engineer of the studied organization with the knowledge of the key parameter of laser welding that could assist in planning and execution of effective resource distribution among parameters. The findings presented here stimulate a high impact potential through a straightforward but precise method that permits the proposed techniques of parametric selection of laser weld parameters to enhance the weld quality of the laser welding process and concurrently ensure the best weld bead geometry to reflect the differences in the weights of the parameters through different methods.

In this article, for the laser welding process of Al-Mg-Mn-Zr-Er alloy sheets, a new approach that compares and priorities the laser welding process parameters of wire feed speed, welding speed and laser power using the AHP, FAHP, entropy, CRITIC and the best-worst method have been proposed for the first time in the welding literature. The highlight of these parameters was previously not considered for the work material considered in the laser welding literature. Therefore, this study enlarges the comprehension of practising engineers and researchers concerning the prioritization of parameters. The novelty of this article is about the application of five multicriteria methods, namely AHP, FAHP, best-worst, entropy and CRITIC to the Al-Mg-Mn-Zr-Er alloy sheets.

Moreover, some additional studies are essential for future studies. First, the present study considered five multicriteria a method, namely, the AHP, FAHP, entropy, best-worst method and CRITIC. These were considered independent of one another. However, the welding literature has justified the combination of the method as more robust than the individual method since the weakness of one could be complemented by the strength of the others. In this respect, the introduction of genetic algorithms (GAs) to couple the five multicriteria methods as AHP-GA, FAHP-GA, entropy –GA, best-worst-GA and CRITIC-GA methods may add to the understanding of the welding process parameters' prioritization while welding the Al-Mg-Mn-Zr-Er alloy sheets. Second, the normalization method has been suggested as important to determining the outcome of a multicriteria method in the literature. But a single but different normalization method was used in those methods requiring normalization in this study. Thus, introducing a new and common normalization method with which comparison with those used presently could be made on the multicriteria method outcome is essential. These results could also be compared with and without the new normalization method for the suggested joint methods involving the genetic algorithms and each of the five methods.

References

[1] AWS C7.41C7.4M: 2017, "An American National Standard, process specification and operator qualification for laser beam welding," *American Welding Society*, 2nd *Edition, June 27, 2017*, Prepared by the American Welding Society (AWS) C7 committee on high Energy Beam Welding and cutting, AWS Technical Activities Committee.

[2] D. A. Jennings, E. D. West, K. M. Evenson, A. L. Rasmussen, and W. R. Simmons, "Technical Note 382, Laser Power and Energy Measurements," *United State Department of Commerce, National Bureau of Standards*, pp. 1-64, 1969.

[3] Industry Research, "2021-2027 Global and regional laser welding and cutting robots industry status and prospects," *Professional Market Research Report Standard Version, SKU* ID: HNY-18831957, 154p, 2021.

[4] T. Webber, T. Lei, J. Mazumder, L. B. Welding, T. In Lienert, T. Siewert, S. Babu and V. Acoff (Eds), "ASM Handbook, Welding Fundamentals and Processes," *ASM International (Volume 6A), Almere, the Netherlands*. DOI: https://doi.org/10.31399/asm.hb.v06a.a0005641, 2011.

[5] S. Katayama, "Handbook of Laser Welding Technologies, Woodhead Publishing," *Cambridge, England*, 2013.

[6] W. M. Steen, J. Mazumder, "Laser Material Processing, SpringerLink. *New York, USA*, doi:10.1007/978-1-84996-062-5. ISBN 978-1-84996-061-8, 2010.

[7] M. Kurtulmus, A. I. Yukler, M. K. Bilici, Z. Catalgol, "Effects of welding current and arc voltage on FCAW weld bead geometry," *International Journal of Research in Engineering and Technology*, vol. 4, no. 9, pp. 23-28, 2015.

[8] D. Yang, X. Li, D. He, Z. Nie, H. Huang, "Optimization of weld bead geometry in laser welding with filler wire process using Taguchi's approach, " *Optics & Laser Technology*, vol. 44, no. 7, pp. 2020-2025, 2012.

[9] L. Bidi, P. Le Masson, E. Cicala, C. Primault, "Experimental design method to the weld bead geometry optimisation for hybrid laser-MAG welding in a narrow chamfer configuration," *Optics and Laser Technology*, vol.89, pp. 114-125, 2017.

[10] B. Choudhury and M. Chandrasekaran, "Multi-optimization of weld bead characteristics during GTAW of Inconel 825 using teaching learning based optimization," *Materials Today: Proceedings*, vol. 46, no. 18, pp. 8958-8963, 2021.

[11] X. Dong, G. Wang and M. Ghaderi, "Experimental investigation of the effects of laser parameters on the weld bead shape and temperature distribution during dissimilar laser welding of stainless steel 308 and carbon steel St 37," *Infrared Physics and Technology*, vol. 116, Article 103774. doi:10.1016/j.infrared.2021, 103774, 2021.

[12] C. M. Horvath, J. Botzheima, T. Thomessen, P. Korondia, "Bead geometry modeling on uneven base metal surface by fuzzy systems for multi-pass welding," *Expert Systems with Applications*, Doi:10,1016/j.eswa.2021.115356, 2021.

[13] S. F. Nabavi, M. H. Farshidianfar, A. Farshidianfar, B. Beidokhti, "Physical-based methodology for prediction of weld bead characteristics in the Laser Edge Welding process," *Optik*, vol.241,Article166917.https://doi.org/10.1016/j.ijleo.2021.166917,, 2021.

[14] W. Tayier, S. Janasekaran and V. P. Vijayasree, "Evaluation of heat input and bead geometry of zincalume steel (G550) welded joint between metal inert gas (MIG) and laser beam welding (LBW)," *Materials Today: Proceedings*, doi: 10.1016/j.matpr. 2021.02.494, 2021.

[15] X. Wei, H. Huang, Z. Chen, W. Wang, C. Li, Z. Nie, "Microstructure and mechanical properties of Al-Mg-Mn-Zr-Er weld joints filled with Al-Mg-Mn-Zr and Al-Mg-Mn-Zr-Er weld wires," *Journal of Rare Earths*, vol. 28, no. 4, pp. 627-630. https://doi.org/10.1016/S1002-0721(09)60168-X, 2010.

[16] D. Yang, X. Li, D. He, H. Huang and L. Zhang, "Study on microstructure and mechanical properties of Al–Mg–Mn–Er alloy joints welded by TIG and laser beam," *Materials & Design*, vol. 40, pp. 117-123, https://doi.org/10.1016/j.matdes.2012.03.041, 2012.

[17] D. Yang, X. Li, D. He and H. Huang, 2013, "Effect of minor Er and Zr on microstructure and mechanical properties of Al–Mg–Mn alloy (5083) welded joints," *Materials Science and Engineering: A*, vol. 561, pp. 226-231. https://doi.org/10.1016/j.msea.2012.11.002, 2013.

[18] X. Lei, H. Huang and H. Wang, "The fatigue crack propagation of Al-Mg-Mn-Zr alloy with erbium," *Advanced Materials Research*, vol. 1120-1121, pp. 1083-1088, 2015.

[19] H. Wu, S. P. Wen, H. Huang, X. L. Wu, K. Y. Gao, W. Wang and Z. R. Nie, "Hot deformation behavior and constitutive equation of a new type Al–Zn–Mg–Er–Zr alloy during isothermal compression," *Materials Science and Engineering: A*, vol. 651, pp. 415-424. https://doi.org/10.1016/j.msea.2015.10.122, 2016.

[20] H. Wu, S. P. Wen, H. Huang, K. Y. Gao, X. L. Wu, W. Wang and Z. R. Nie, "Hot deformation behavior and processing map of a new type Al-Zn-Mg-Er-Zr alloy," *Journal of Alloys and Compounds*, vol. 685, pp. 869-880. https://doi.org/10.1016/j.jallcom.2016.06.254, 2016.

[21] D. Wu, N. Wang, Z. Yang, C. Li, Y. Yang, "Comprehensive evaluation of coal-fired power units using grey relational analysis and a hybrid entropy-based weighting method," *Entropy*, vol. 20, pp.215, 2018.

[22] D. Yang, X. Li, D. He, Z. R. Nie and H. Huang, "Microstructural and mechanical property characterization of Er modified Al–Mg–Mn alloy tungsten inert gas welds," *Materials & Design*, vol. 34, pp. 655-659. https://doi.org/10.1016/j.matdes.2011.05.022, 2012.

[23] Z. Zhang, S. Dong, Y. Wang, B. Zu, J. Fang and P. He, "Microstructure characteristics of thick aluminum alloy plate joints welded by fiber laser," *Materials & Design*, vol. 84, pp. 173-177, DOI:10.1016/j.matdes.2015.06.08, 2015.

[24] H. Wu, S. P. Wen, H. Huang, B. L. Li, X. L. Wu, K. Y. Gao, W. Wang and Z. R. Nie, "Effects of homogenization on precipitation of Al_3(Er,Zr) particles and recrystallization behavior in a new type Al-Zn-Mg-Er-Zr alloy," *Materials Science and Engineering: A*, vol. 689, pp. 313-322. https://doi.org/10.1016/j.msea.2017.02.071, 2017.

[25] A. P. Aravind, J. S. Kurmi, P. M. Swamy, S. R. Kumar, S. Rajak and T. D. B. Kannah, "Optimisation of welding parameters in laser welding of Ti6Al4V using VIKOR optimisation method," *Materials Today: Proceedings*, vol. 45, no. 2, pp. 592-596, doi:10.1016/j.matpr.2020.02.388, 2021.

[26] M. S. Khan, S. I. Shahabad, M. Yavuz, W. W. Duley, E. B. Y. Zhou, "Numerical modelling and experimental validation of the effect of laser beam defocusing on process optimisation during fiber laser welding of automotive press-hardened steels," *Journal of Manufacturing Process*, vol 67, pp. 535-544. DOI:10.1016/j.jmapro.2021.05.006, 2021.

[27] Y. Huang, X. Gao, B. Ma, G. Lui, N. Zhang, Y. Zhang, D. You, "Optimisation of weld strength for laser welding of steel to PMMA using Taguchi design method," *Optics and Laser Technology*, vol. 136, Article 106726, doi:10.1016/j.optlastec.2020.106726, 2021.

[28] M. Hietala, M. Ali, A. Khosravifard, M. Keskitala, A. Jarvenpaa and A. Hamda, "Optimisation of the tensile shear strength of laser-welded lap joints of ultra-high strength abrasion resistance steel," *Journal of Material Research and Technology*, vol. 11, pp. 1434-1442, doi:10.1016/j.jmrt.2021.01.121, 2021.

[29] T. D. B. Kannan, A. P. Aravind, P. Sathiya, "Experimental investigation and optimisation of process parameters in laser welding of Nitinol shape memory alloys," *Materials Today: Proceedings*, vol. 22, no. 4, pp. 1563-1571, doi:10.1016/j.matpr.2020.02.118, 2020.

[30] S. Datta, M. S. Raza, A. K. Das, P. Saha, D. K. Pratihar, "Experimental investigations and parametric optimization of laser beam welding of NiTinol sheets by metaheuristic techniques and desirability function analysis," *Optics and Laser Technology*, vol. 124, Article 105982, doi: 10.1016/j.optlastec.2019.105982, 2020.

[31] Z. Lei, J. Shen, Q. Wang, Y. Chen, "Real-time weld geometry prediction based on multi-information using neural network optimized by PCA and GA during thin-plate laser welding," *Journal of Manufacturing Processes*, vol. 43, no. 10, pp. 207-

217. DOI: 10.1016/j.jmapro.2019.05.013, 2019.

[32] K. R. Sampreet, V. Mahidhar, R. Kannan, Arunagiri and T. D. B. "Optimization of parameters in Nd:YAG laser welding of Ti-6Al-4V using TOPSIS, Materials Today: Proceedings," vol. 21, no. 1, pp. 244-247, https://doi.org/10.1016/j.matpr.2019.05.401, 2020.

[33] Y. Yang, Z. Gao and L. Cao, "Identifying optimal process parameters in deep penetration laser welding by adopting Hierarchical-Kriging model," *Infrared Physics and Technology*, vol. 92, pp. 443-453, doi: 10.1016/j.infrared.2018.07.006, 2018.

[34] U. Reisgen, M. Schleser, O. Mokrov, E. Ahmed, "Optimization of laser welding of DP/TRIP steel sheets using statistical approach," *Optics and Laser Technology*, vol. 44, no. 1, pp. 255-262, doi: 10.1016/j.optlastec.2011.06.028, 2012.

[35] P. Zhang, Z. Jia, Z. Yu, H. Shi, S. Li, D. Wu, H. Yan, X. Ye, J. Chen, F. Wang and Y. Tian, "A review on the effect of laser pulse shaping on the microstructure and hot cracking behavior in the welding of alloys," *Optics & Laser Technology*, vol. 140, Article 107094, https://doi.org/10.1016/j.optlastec.2021.107094, 2021.

[36] Y. Qu, Z. Li, J. Li, D. Zou, R. Zhang and Y. Yu, "Effect of weld geometry parameters on dynamic behavior of buried X70 steel pipeline under subsurface detonation," *International Journal of Pressure Vessels and Piping*, doi: 10.1016/j.ijpvp.2021.104504, 2021.

[37] V. Paranthaman, D. Veeman and V. S. Mahesh, "Optimization of CO_2 welding process on dissimilar metals," *Materials Today: Proceedings*, vol. 39, doi: 10.1016/j.matpr.2020.07.694, 2020.

[38] S. Grünenwald, A. Unt and A. Salminen, "Investigation of the influence of welding parameters on the weld geometry when welding structural steel with an oscillated high-power laser beam," *Procedia CIRP*, vol. 74, pp.461-465, https://doi.org/10.1016/j.procir.2018.08.150, 2018.

[39] C. Prieto, E. Vaamonde, D. Diego-Vallejo, J. Jimenez, B. Urbach, Y. Vidne and E. Shekel, "Dynamic laser beam shaping for laser aluminium welding in e-mobility applications," *Procedia CIRP*, vol. 94, pp. 596-600. https://doi.org/10.1016/j.procir.2020.09.084, 2020.

[40] Z. Guo, R. Bai, Z. Lei, H. Jiang, J. Zou and C. Yan, "Experimental and numerical investigation on ultimate strength of laser-welded stiffened plates considering welding deformation and residual stresses," *Ocean Engineering*, vol. 234, Article 109239, https://doi.org/10.1016/j.oceaneng.2021.109239, 2021.

[41] S. K. Gupta, S. Jaypuria, D. K. Pratihar, P. Saham, "Study on mechanical and metallurgical properties of fiber laser welded Nb-1% Zr-0.1% C alloy," *Optics & Laser Technology*, vol. 127, Article 106153, 2020.

[42] S. M. Robertson and A. F. H. Kaplan "Multi-keyhole separation during multi-spot laser welding of duplex steel," *Optics and Laser Technology*, vol. 143, 2021.

[43] P. M. Mashinini, D. G. Hattingh, "Influence of laser heat input on weld zone width and fatigue performance of Ti-6Al-4V sheet," *Materials Science and Engineering B*, vol. 262, Article 114699, doi: 10.1016/j.mseb.2020.114699, 2020.

[44] V. Errico, S. L. Campanelli, A. Angelastro, M. Mazzarisi and G. Casalino, "On the feasibility of AISI 304 stainless steel laser welding with metal powder," *Journal of Manufacturing Processes*, vol. 56, pp. 96-105, https://doi.org/10.1016/j.jmapro.2020.04.065, 2020.

[45] S. Liu, F. Liu, H. Zhang, Y. Shi, "Analysis of droplet transfer mode and forming process of weld bead in CO2 laser–MAG hybrid welding process," *Optics & Laser Technology*, vol. 44, no. 4, pp. 1019-1025. https://doi.org/10.1016/j.optlastec.2011.10.016, 2012.

[46] T. Sathish, S. D. Kumar, K. Muthukumar and K. Suyambu K. "Natural inspiration technique for the parameter optimization of A-GTAW welding of naval steel," *Materials Today: Proceedings*, vol. 21, doi: 10.1016/j.matpr.2019.07.600, 2019.

[47] X. Chen, G. Yu, X. He, S. Li and Z. Li, "Numerical study of heat transfer and solute distribution in hybrid laser-MIG welding," *International Journal of Thermal Sciences*, vol. 149, Article 106182. doi: 10.1016/j.ijthermalsci.2019.106182, 2020.

[48] M. Şahin, "A comprehensive analysis of weighting and multicriteria methods in the context of sustainable energy," *International Journal of Environmental Science and Technology*, vol. 18, pp. 1591–1616, https://doi.org/10.1007/s13762-020-02922-7, 2021.

[49] V. M. Ozernoy, "Choosing the “Best” multiple criteria decision-making method," *Information Systems and Operational Research*, vol. 30, pp. 159–171. https://doi.org/10.1080/03155986.1992.11732192, 1992.

[50] A. Ishizaka, S. Siraj, "Are multi-criteria decision-making tools useful? An experimental comparative study of three methods," *European Journal of Operational Research*, vol. 264, pp. 462–471, https://doi.org/10.1016/j.ejor.2017.05.041, 2018.

[51] M. Haddad and D. Sanders, "Selection of discrete multiple criteria decision making methods in the presence of risk and uncertainty," *Operations Research Perspectives*, vol. 5, pp. 357–370, https://doi.org/10.1016/j.orp.2018.10.003, 2018.

[52] R. Mosadeghi, J. Warnken, R. Tomlinson, H. Mirfenderesk, "Uncertainty analysis in the application of multi-criteria decision-making methods in Australian strategic environmental decisions," *Journal of Environmental Planning and Management*, vol. 56, pp. 1097–1124, https://doi.org/10.1080/09640568.2012.717886, 2013.

[53] I. Yukler and I. Calis, "Weld Bead Geometry," *MUTEF Publications, İstanbul*, 1999.

[54] J. Matys, M. Dominiak and R. Flieger, "Energy and power density: A key factor in lasers studies," *Journal of Clinical and Diagnostic Research*, vol. 9, no. 12, pp. ZLO1-ZL02. doi: 10.7860/JCDR/2015/1556.6955, 2015.

[55] R. Kant, S. N. Joshi and U. S. Dixit, "Research issues in the laser sheet bending process," *in Materials Forming and Machining*, pp. 73-97, doi: 10.1016/b978-0-8570-483-4.000041, 2016.

[56] T. L. Saaty, "Decision making with the analytic hierarchy process," *International Journal of Services Sciences*, vol. 1, no. 1, pp. 83–98, 2008.

[57] K. O. Okponyia and S. A. Oke, "Exploring aluminium alloy metal matrix composites in EDM using coupled factor-level-present worth analysis and fuzzy analytic hierarchy process," *International Journal of Industrial Engineering and Engineering Management*, vol. 2, no. 1, pp. 25-44, 2020.

[58] M. Singh M. and R. Rathi, "Investigation on critical success factors associated with lean six sigma implementation in MSMEs using best-worst method," *International Journal of Six Sigma and Competitive Advantage*, vol. 12, no. 2/3, pp. 209-233. doi: 10.1504/IJSSCA. 2020. 110976, 2020.

[59] V. Raghunathan, R. Ranganathan and M. Palamisamy, "An efficient supplier selection model for the pump industry through the best-worst method," *International Journal of Services and Operations Management*, vol. 28, no. 3, pp. 360-378. doi:10.1504/IJSONA2021.113601, 2021.

[60] J. Liang, Z. D. Shi, M. J. Wierman, "Information entropy, rough entropy and knowledge granulation in incomplete information systems," *International Journal of General Systems*, vol. 35, pp. 641–654, 2006.

[61] H. Zhao, L. Yao, G. Mei, T. Liu and Y. Ning, "A Fuzzy comprehensive evaluation method based on AHP and entropy for landslide susceptibility map," *Entropy*, vol. 19, pp. 396, 2017.

[62] N. M. Raffic, K. G. Babu, S. Srinivasan, S. Thirumurugaveerakumar and R. B. Kanna, "Experimental investigation on surface roughness and cutting tool – Workpiece interface temperature for AA6061 using CRITIC and TOPSIS techniques," *Materials Today: Proceedings*, In press, https://doi.org/10.1016/j.matpr.2021.05.145, 2021.

[63] X. Dong, H. Lu, Y. Xia, Z. Xiong, "Decision-making model under risk assessment based on entropy," *Entropy*, vol. 18, pp. 404, 2016.

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