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Multicriteria Selection of Friction Stir Welded Al-Tib$_2$ Metal Matrix Composites using WASPAS to Improve Composite Development and Design

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ABSTRACT

The unique area of friction stir welding that involves Al-TiB2 composite development stirs controversy and fails to offer a clear understanding of how to choose the best composite among alternatives without subjectivity. At present, the experienced fabricator uses intuition in judgement, leading to wrong or inconsistent decisions. In this paper, the WASPAS multicriteria model is deployed to choose the best Al-TiB2 composite among options using tensile strength, ductility and microhardness as attributes. The procedure generally entails normalization, preference score and ranking determination and literature data was used. The emerging conclusion from this study is that irrespective of the weight determination method and the multicriteria model adopted to evaluate the alternative fabricated Al-TiB2 composites, the Al-10%TiB2 and Al6065 based alloy always reveal as the best and worst composites, respectively, even under varied normalisation methods. The research confirmed that multicriteria analysis is a potential objective method to choose among fabricated alternatives. The work showed that there is scope to evade the consequences of subjectivity in composite decision making by attaching adequate weights to the deciding factors thereby avoiding misguidance and incorrect decision making. Furthermore, multicriteria models offer novel approaches to understand the relative preference of fabricating composites to one another in the metal matrix composite development area.

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1. INTRODUCTION

In research concerning the friction stir welding of aluminium metal matrix composite, the selection is a promising and critical issue. It explains the effectiveness of the responses created by the frictional heating of the workpiece as the revolving-translating tool strokes alongside the workpiece. This is distinctive from the intuition judgment of the machine workshop manager (Christy, 2010; Kishan et al., 2017; Kishan and Devaraju, 2017; Li et al., 2018; Karloopia et al., 2018; Balaji et al., 2018; Barati et al., 2019; Karpasand et al., 2020). Selection predicts the composite that will endure a long lifespan, adding accuracy to the manager's understanding of the shear and normal forces' dynamic blend. It is demonstrated in the tool's rotational speed, travel speed, and pressure in a friction-stir welding endeavor (Vijay and Murugan, 2010; Sharma et al., 2019). As defined here, the selection is the extent to which a chosen composite type satisfies an optimal combination of tensile and metallurgical parameters of the composites. It is regarded as the response to the heating process of the friction stir welding of the composite (Vijay and Murugan, 2010; Chen et al., 2019).

Selection influences composite structural design and is an essential constituent of structural development, monitoring and control during the composite's lifespan. Unfortunately, there is no study on selecting the best composite as Al-6061 base alloy is welded with various proportions of TiB_2 metal through the friction stir welding process. Further, as currently demonstrated in practice, the objective procedure of selecting the Al-TiB_2 composite may not be understood through the existing trial-and-error approach. With the wide options of composites in new composite development endeavors, the deficiency in the current selection process restricts the composite developer's skill. Researchers are unable to exploit the potentials of the developed composites completely. Currently, the engineering community has advanced in the knowledge base of multicriteria analysis, and the community can model how to select materials at different echelons of product development. It is then appropriate that composite researchers judge how to implement this significant type of knowledge variety (Bitarafan et al., 2014). Consequently, in this paper, the novel decision making a multicriteria model of WASPAS was used. It examines the tensile and metallurgical test data for an objective analysis of Al-6061 base alloy welded with the friction stir process. This work bridges two literature domains – friction stir welding and composite. It connects both literature areas to analyze the influence of selection on the process that integrates them.

This paper targets an important area of manufacturing that interfaces between friction stir welding and composite manufacturing. It addresses the welding of Al6061 base alloy to varying proportions of TiB_2 metal in a metal matrix composite development exercise. The situation exists that several samples are fabricated. Fabrication depends on the applications which require significantly attractive mechanical properties and strong wear resistance. Furthermore, it was decided to test samples using tensile tests (ultimate tensile strength and percentage ductility) and metallurgical test (microhardness). Having different values of tensile and metallurgical parametric quantities, there is a complication in choosing the best sample from this group. Hence, the WASPAS model was found to be an appropriate objective tool to select the specimen.

To this end, this paper examines how the theory of WASPAS multicriteria is applicable. WASPAS is preferred for subjective intuition actions and experience. It can contribute to sound composite selection and decision making in friction stir welding by leaning on experts who decide on the importance scale. By focusing on objectivity in the choice of the Al-TiB_2 composites, the WASPAS approach in which Zavadskas et al. (2013a), described as highly reliable with ranking accuracy, is adopted (as opposed to intuition and the experience of the composite developer) to conceptualize the composite selection process. The WASPAS approach represents an extremely useful route by explaining in quantitative terms how the number of criteria and attributes as well as the importance scale is determined. In contrast, the intuition approach emphasizes trial and error reasoning.

In its eight years of existence, the WASPAS multicriteria has been used in several applications, and it has survived as a choice method among competing models such as ELECTRE, SWARA, MODM, SAW, BWM, TOPSIS, AHP,

DEMATEL, PROMETHEE, VIKOR, DEA, LINMAP, COPRAS, MULTIMOORA, MOORA, ARAS, EDAS and their fuzzified versions (Mardani et al., 20017). WASPAS is preferred to other multicriteria models due to its distinctive features (Alinezlad and Khalili, 2019): First, it can compare quality terms and translate them into numerical expressions. Second, it is reputed as rewarding. Third, the characteristics are autonomous. These features are incorporated into the composite selection strategy.

The intuition approach is currently approved to account for the selection process of the Al-TiB_2 composite. However, due to composite properties' multi-attribute nature, intuition-based selection strategy may not offer a realistic approach. The settings used in this article integrate the tensile and metallurgical properties of the Al-TiB_2 samples. The settings were built up based on the logical approach offered in literature by Zavadskas et al. (2013a). Likewise, the WASPAS model seeks expert inputs of the friction stir welding and composite development communities via importance rating. Consequently, this method offers a superior decision weighed against the intuition approach.

Furthermore, the focus is on Al-TiB_2 metal matrix composites because they are extensively used in numerous industries, including structural, automobile, aerospace, and naval vessels (Suresh et al., 2012; Vajagah et al., 2014; Chen et al., 2017; Pahdpilli et al., 2018). Although Al-TiB_2 composites have been studied in diverse perspectives such as wear (Poria et al., 2018), vibration (Wang et al., 2019; Zhao et al., 2020), and machining (Magibalan et al., 2019), as noticed in previous literature, there is a complete absence of knowledge on the objective perspective of ranking and choosing the best Al-TiB_2 composites from the various Al.wt.% composites using the criteria of ultimate tensile strength, microhardness and ductility in the friction stir casting technique of production (Kishan and Devaraju, 2017; Kishan et al., 2017; Karloopia et al., 2018; Mozammil et al., 2020; Sethi et al., 2020; Karpasand et al., 2020).

As industries are confronted with business collapse threats resulting from wrong decision making based on the wrong choice of product options, a scientific rethinking is necessary. Also, as industries experience inconsistent results based on intuition in product choices, now is a suitable time to solve the problem of choosing the best product from alternatives. This work's results may be useful to fabricators and production planning managers that wish to follow objective planning schemes for their systems. In this investigation, analysis of the criteria, namely, ultimate tensile strength, ductility, and microhardness, are re-considered for the Al-TiB2 MMCs with Christy's literature data (2010) explored. New conclusions are derived from the earlier results.

2. LITERATURE REVIEW

Before the emergence of friction stir welding (FSW) in 1991, welding practices had been limited to the conventional welding (fusion) technique, which is extremely problematic (Karloopia et al., 2018). However, the breakthrough technology of FSW, patented by TWI, provided a profitable route to evade the problematic nature of conventional welding technique (Karloopia et al., 2018; Bocchi et al., 2018, Li et al., 2018; Sharma et al., 2019). As the FSW became the centre of attraction in the scientific community, success was achieved as FSW showed the capability to join aluminium alloys. Soon, this success was limited and a wide range of possibilities was proposed. The FSW scope then expanded to join all series of aluminium alloys, magnesium alloys, steels, Ni-base superalloys, and Ti alloys (Li et al., 2018).

By counting the gains of FSW, the research community appreciates the tremendous leap in productivity due to the adoption of FSW against the conventional technique of fusion welding. For instance, when knowledge was limited to fusion welding, the welding community was confronted with problems associated with reinforcement segregation, irregular spread, undesired reactions and defects (oxide creation at elevated temperature, and porosity) (Karloopia et al., 2018). However, the FSW breakthrough has brought enviable properties in welding and welding products, including energy efficiency, avoidance of solidification defects and grain refinements (Sharma et al., 2019). Furthermore, the installation of standard welding procedures in industries, such as ISO 25239-4: 2011, has permitted manufacturers and researchers to benefit from the FSW process (Sharma et al., 2019).

In the past, many literature reviews were approached by analyzing the composites developed. Analyses were based on the methodology utilized in the composite development and the general contribution of the papers with a clear understanding of the reinforcements that constitute the composites. At variance with this review approach, a careful attempt was made here to identify the major types of reinforcements used in FSW experiments for metal matrix composites. It is amazing to note the broad array of metal matrix reinforcements in FSW to include the following: SiC, Al_2O_3, B_4C, TiB_2, Al_2O_4, Ti, Cu and flyash**.** However, they were found to be applied in different composites in diverse proportions as reinforcements. A brief review of reinforcement applications include the following: The reinforcement Cu, is one of the very few elements mixed with metal matrices as in AA2198-T851 Al-Cu-Li alloy (Donatus et al., 2018), and AA2219(Al-Cu-Mg alloy) (Balaji et al., 2018).

While these examples have their primary alloys in the 2xxx series aluminium alloys, it confirms the literature proclaims of the 2xxx series as outstanding lightweight composites in the engineering fields of electronics, automobile, shipbuilding and aerospace due to their light density, fracture toughness, minimum cost, fairly elevated strength and outstanding workability (Li et al., 2018; Balaji et al., 2018; Yang et al., 2019). In fact, beyond the Cu reinforcement application in the 2xxx series aluminium alloy, the Al_2O_3 reinforcement has also shown some promise as evident in AA2024/Al_2O_3 (Yang et al., 2019). Furthermore, the reinforcement TiB_2 is known to be an extremely useful metal matrix composite for the FSW process.

The classic studies concerning Al-TiB_2 (Sharma et al., 2019), Al-10%wt TiB_2 (Vijay and Murugan, 2010), and on $(TiB_2)_p$6061-T6 (Kishan and Devaraju, 2017) have some interesting results on FSW. At the beginning of research on composite development in FSW, single reinforcements were the dominant substances but later researchers explored the synergic powers of two reinforcements in FSW activities, such as AA7005/TiB_2-B_4C (Pol et al., 2019) and Al-Si-TiB_2 (Karloopia et al., 2018). A further study reveals the use of AZ31B magnesium alloys to reinforce AA6061 aluminium matrix (Jayarai et al., 2017). Several theories have been used to explain the characterization and behaviour of metal matrix composites when subjected to friction stir welding (Sharma et al., 2018; Sharma et al., 2019).

These theories include corrosion (Sharma et al., 2019; Senthil and Ballasubramanian, 2019), and mechanics (Balaji et al., 2019). In the area of composite welding in FSW, Li et al. (2018) discussed issues on the following: corrosion resistance of joints in FSW, spraying water on the welding tools to carefully choose the welding indices, and to cool the composites with cryogenic substances, the use of spray coatings, heat treatments at the post-weld instances, oxidation of micro-arc and adjustments of surfaces. Other theories brought into the FSW area are hardness (Balaji et al., 2018), and wear (Sharma et al., 2018; Barati et al., 2019).

The rationale for the review of literature conducted in this section entails describing the literature regarding the Al-60661 base alloy welded with property modifiers such as SiC, Al_2O_3, B_4C, TiB_2, Al_2O_4, Ti, Cu and flyash but with a keen interest in TiB2 and further additives in welding under the friction stir welding process. The rationale also covers to offer a summary and carry out a crucial appraisal of the contributions and then associate them to the problem of selecting the best Al-TiB_2 composite. In this review, an attempt was made to determine previous scholarship in the welding of Al-6061 base alloy with TiB_2 modifiers and the analysed papers were considered only on the fact that the articles deepen researchers' understanding on the friction stir welding of Al-6061 base alloy with TiB_2 in diverse proportions.

In this study, significant efforts were made to gain insight to and solve the composite selection because of its importance in composite development and design. Tackling the composite selection problem is essential for several reasons. First, resources in the control of composite developers are multicriteria, increasingly becoming limited, and their optimal usage is essential for the sustenance of fabrication operations and to justify the professional competence of the fabricators, composite developers and engineers. To this end, to manage this multicriteria problem in an extremely efficient way composite developers and engineers appear to use multicriteria models. For instance, in friction stir welding, tools, energy and process manhours, which are multicriteria gets consumed and their replacements tend to match a multicriteria solution pattern. Also, welding specimens are limited and the composite developer is compelled to renew them. Second, selecting the appropriate composite option is challenging and following scientific procedures enhances the developer's understanding of the process and materials. This offers a substantial motivation to composite developers towards sustenance drive for the system.

The decision making community has recently drawn the interest of many composite development scholars to a new multicriteria model, WASPAS, which it suggests carries substantial implications for how composite developers and designers go about handling information. Mardani et al. (2017), one of the advocates of WASPAS, declared that it aids deep insights into stakeholders' inclinations, unified or inconsistent measures, and uncertain situations.

Zavadskas et al. (2012) built up WASPAS as a multidimensional model and argued that it derives its strength from the synergic contribution of WSM and WPM, elevating it to higher accuracy than competing multicriteria models. Mardani et al. (2017) offered a comprehensive review concerning the trends in WASPAS' applications over the years. This is repeated here to concur to the review. The review reveals the adventure in the application of WASPAS initially driven by the Zavadskas research team in several areas: Bagocius et al. (2013b) demonstrated a feasible route to choose a deep-rooted water pot using WASPAS; Staniunas et al. (2013c) achieved success with WASPAS to appraise manifold-dwelling modernization regarding environmental-economic dimensions; Zavadskas et al. (2013b) deployed WASPAS to appraise options when dealing with facades.

A broad array of applications, models, and experimental approaches have been proposed in the friction stir welded composite development literature to reveal the attributes of the Al-6061 base alloy when welded with TiB_2 or similar mechanical and wear property enhancement tools. An outcome of the literature review is the following groundwork information. But the technical details derived from this information built into the present research:

a. Friction stir welding offers a unique solid-state process in a very straightforward and fast-joining process.
b. Friction stir welding is promising in processing composites while its energy efficiency and the process is highly acceptable.
c. Multicriteria models have been claimed to offer effective decision-making impacts in many applications in both the friction stir welding and the composite manufacturing areas
d. The use of TiB_2 additive in Al60661 alloys in the context of friction welding of the additive and alloys connects the metal matrix composite and friction stir welding research communities with industry, offering promising opportunities for new developments in methodologies and practices
e. The use of WASPAS multicriteria model in the friction stir welding of Al-8081 alloys or Al-6061 alloys welded with portions of TiB_2 compound has not been studied
f. WASPAS method is preferred to WSM and WPM from the accuracy angle of reasoning
g. WASPAS method is one of the extremely reliable multicriteria techniques developed in recent times
h. TiB_2 is a suitable reinforcement agent for Al-6061 alloys given its high wear and mechanical properties

3. RESEARCH METHOD

3.1. Critical parameters considered

The critical elements of the WASPAS method are expressed both in qualitative and quantitative nature. They include the number of criteria (attributes), the number of options, the weights of the attributes, the importance rating, among others. The number of criteria is quantitative and represents the number of attributes of interest. In this paper, tensile strength is though to be critical in the determination of the life of composite. Tensile strength is the utmost stress that the Al-TiB_2 composite can endure while being stretched or pulled ahead of breakage. With the tensile strength, the designer will be capable to control the ability of the composite structure for variations in design loads throughout the operational life of the structure. As such, it is recorded as a first critical data set to be analysed in this work through the use of the ultimate tensile strength parameter.

Furthermore, ductility, the property of the Al-TiB_2 composite to endure tensile stress without becoming more brittle in the procedure is also taken as important in the analysis considered here. The third property of importance is microhardness, which concerns the hardness of the Al-TiB_2 composite as established by compelling an indenter, including Vickers indenter hooked to the surface of the Al-TiB_2 composite when subjected to roughly a load range of 15 to 1000 gf. In this context, the three properties of ultimate tensile strength, percentage ductility and microhardness are important for the selection of the Al-TiB2 composite among its variants.

Besides, literature provides data for use in the analysis with the WASPAS model proposed in the present study. In this paper, it was thought that tensile test and metallurgical test results, which together yields values of three different attributes of ultimate tensile strength, percentage ductility and microhardness values of the specimens are good representatives of the major desirable attributes that the Al-6061 base alloy and Al-6061 base alloy with Al-TiB_2 mixture can be judged. The number of options is the different samples to compare with and this is a quantitative metric. In the present study, based on the literature data of Christy (2010) that forms the data used to validate the WASPAS model, four alternatives are considered. These are the Al-6061 base alloy, Al-6%TiB_2, Al-8%TiB_2, and Al-10%TiB_2. The importance rating is qualitative and this is the expert's judgement given by some experienced fabricator in the aluminium metal composite area and also conversant with the friction stir welding process.

3.2. Multicriteria analysis on composite

As the metal matrix composite (MMC) literature matures, there is an adequate critical knowledge in research and practice to justify the growth of more detailed and cohesive mechanical and wear enhancement and selection strategies. But in the friction stir welding field that uses Al-60661 alloy welded with varying percentages of TiB_2, it becomes extremely difficult for a newly employed composite development engineer and designer to achieve accuracy and carry out unbiased decisions during welding. Mastery of the frictional heat control between the tool and the workpiece to attain a solid-state bond of the workpieces is not sufficient alone. Also, success to choose the correct composite option is compulsory. At present, current knowledge allows the designer to choose the Al-6061 alloy welded with TiB_2 compound option for the subsequent design of products by an arbitrary means and the choices made by different experienced developers and designers may vary.

However, although successful choice may be made through trial and error method where the attributes of the Al-6061 alloy infused with Al-TiB_2 are considered, how the designer removes bias in the selection process is not yet tackled in the MMC literature. This finding reveals that as long as this research and practice gap persists the industry is at risk of producing sub-standard products through wrong choices from the poorly scientific process. Therefore, to obtain optimal decisions and making reliable judgements, novel and innovative computational tools are necessary. This article offers a unique approach to eliminate bias in the alternative composite selection process. This novel approach is based on the weighted aggregated sum product assessment (WASPAS), which allows the composite developer to create a robust development procedure through a four-stage process of developing, normalize, compute and evaluate the composite attributes. Accordingly, the WASPAS theory that is based on the four pillars mentioned above is deployed. The assessment matrix was first developed with the content formed from an expert(s)' ideas generated through interactions. The matrix is then normalised to eradicate duplication and unwanted attributes as well as to ascertain that data reliance is sensible (Vafaei et al., 2016). Afterwards, the WSM and WPM are computed from the rule of summation of additive and product of the comparative importance of the Al-TiB_2 MMC criteria and finally, the evaluation of the comparative importance for each option is made. The central idea of WASPAS multicriteria modelling in Al-TiB_2 MMC selection is to explain a phenomenon whereby an importance rating principle deployed on the variable attributes of the Al-TiB_2 MMCs, indicating preference in terms of the value over the other, and finally emerging with an ordered class of Al-TiB_2 MMCs with the highest and least values indicated by option

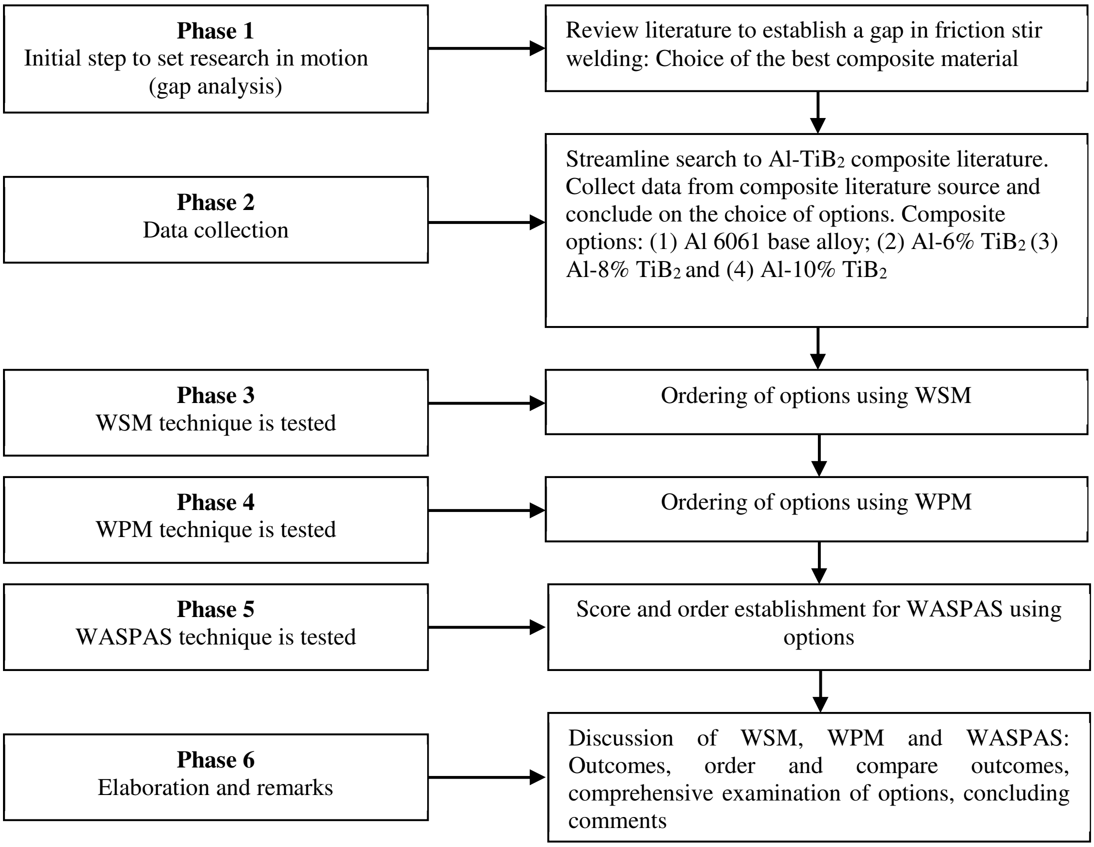

Fig. 1. Phases involved to appraise Al-TiB_2 composite options in friction stir welding

3.3. Research scheme

Multicriteria decision making approaches are developed to respond as effective confrontation tools to choose the best Al-TiB_2 composite in the welding of Al-6061 alloys with varying TiB_2 additives in the friction stir welding process, considering the multi-attributes of the composite. The best option is often established by examining the extent and weights of the attributes and choosing the utmost one by employing the WASPAS method in this article. The complete step-by-step analysis of the Al-TiB_2 composite choice appraisal for the fabrication using WASPAS is shown in Fig. 1.

3.4. WASPAS technique

Multicriteria decision making (MCDM) techniques are incredibly informative tools used daily for managerial tasks in the composite manufacturing plants. However, establishing a satisfactory explanation concerning the dominant parameters that are attached to the goal of interest is an extremely stressful assignment. For example, in the Al-TiB_2 composite manufacturing domain where the primary material, Al-6061 base alloy, is welded with 6 – 10%TiB_2 compound to obtain an option with the most enhanced mechanical and wear properties, an agreeable account about the most influential parameters of the ultimate tensile strength (MPa), percentage ductility of the material and the micro hardening is a tremendously hectic mission. In this article, the novel WASPAS technique has been deployed to resolve this difficult task. This section of the article discusses the methodology involved in solving the problem.

Problem definition:

The problem of composite selection in the perspective of the application of WASPAS model in a multicriteria framework is described as consisting of g options and h decision attributes. The comparative significance, indicating the weight of the attribute is symbolized by w_j. The variable t_{ij} means the performance worth of option i during its appraisal regarding criterion j.

Ghorabaee et al. (2016) proposed a comprehensive step-by-step procedure in implementing WASPAS, which was validated in the classic report of Bid and Siddique (2019). These steps are however used here (Ghorabaee et al., 2016; Bid and Siddique, 2019):

Phase 1: Establish the decision matrix

The original framework that starts the computation in WASPAS is the decision matrix revealed as:

$$\begin{bmatrix} t_{11} & t_{12} & \cdots & t_{1h} \\ t_{21} & t_{22} & \cdots & t_{2h} \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ t_{g1} & t_{g2} & \cdots & t_{gh} \end{bmatrix}$$

where the number of options is represented as g while the number of criteria is shown as h. Furthermore, T_{ij} is the accomplishment of the i^{th} option regarding the j^{th} criteria. The options evaluated are as follows:

Table 1. Options regarding the Al-TiB_2 composite for WASPAS analysis according to Christy's contribution

Option	Description
1	Al 6061 base alloy
2	Al-6% TiB_2
3	Al-8% TiB_2
4	Al-10% TiB_2

These options are the limits provided by Christy (2010) on which the experimental results have been provided.

Phase 2: Normalise (standardize) the decision matrix

Normalization of Al-TiB_2 composite data involves an attempt to arrange the composite fabrication data and make it regular, usually carried out in a matrix form. As an organized decaying data table method to eradicate duplication and unwanted attributes, normalization is pursued to ascertain that data reliance is sensible. In a multicriteria analysis, normalization is deployed to permit amassing criteria through numerical and equivalent data (Vafaei et al., 2016). Several normalization techniques are used in the multicriteria analysis, including the min-max, z-score, and more. Although the z-score is preferred by several researchers as the technique is claimed to conserve range (i.e., maximum and minimum). It is also credited to possess the attribute to indicate the sequence's dispersion, defined as the ratio of the standard deviation to variance. Nonetheless, the min-max method is less complicated and adopted for computation in this work. Besides, as this research has the potential to be merged with the artificial neural networks in future improvement studies, and the min-max method is strongly recommended for analysis using artificial neural networks, this provides additional justification for the use of the min-max method in this work. The standardized values are shown in Table 1, calculated using Equations (1) and (2).

$$\bar{t}_{ij} = \frac{t_{ij}}{t_{ij}^{\max}} \qquad (1)$$

Equation (1) is referred to as the advantageous criteria, which implies that a criterion is advantageous if its growth will result in a positive contribution to the system. However, the opposite of this idea is Equation (2):

$$\bar{t}_{ij} = \frac{t_{ij}^{\min}}{t_{ij}} \qquad (2)$$

This Equation (2) is termed a representation of the non-advantageous criteria.

From Equations (1) and (2), $\bar{t}_{ij}$ is the ratio of the actual criterion value to the value of the maximum criterion value for Equation (1), $\bar{t}_{ij}$ is the ratio of the minimum criterion value to the value of the actual criterion value for Equation (2), in the array, $t_{ij}^{\max}$ is the maximum criterion value and the $t_{ij}^{\min}$ is the minimum criterion value.

This Equation's characteristic is that any increase in the value of its outcome is detrimental to the progress of the system of composite fabrication. It may mean the reduction of an important element in a composite when increased will limit the quantity desired. Equations (1) and (2) are sometimes referred to as beneficial and non-beneficial criteria, respectively in several research reports on multicriteria analysis. The standardized values in the decision matrix are shown in Table 2.

Table 2. Application of beneficial and non-beneficial ratios to original data

	Explanation	**UTS, MPa**	**% Ductility**	**Micro hardening**
Options	Al 6061 base alloy	0.6774	0.5754	0.9119
	Al-6% TiB_2	0.7596	0.6863	0.9523
	Al-8% TiB_2	0.8231	0.7724	0.9733
	Al-10% TiB_2	1	1	1

Phase 3: Calculation of WSM and WPM

Relative importance is a term often deployed in multicriteria analysis to compare the quality attributes of two indicators at a time. In developing a relative importance index, the assessor(s), usually experts related to composite development, are asked to establish their judgements, which simulate actual life situation in materials science and engineering. At this instance, the assessor is compelled to select on the background that perfection does not exist, and the composite assessor should prefer one attribute to the other, or at least give two attributes equal importance. The entire relative importance of the i^{th} option in the composite list is calculated on the account of weighted sum and weighted product approach that is computed on the account of Equations (3) and (4), correspondingly:

$$\text{WSM} = Z_i^{(1)} = \sum_{j=1}^{h} \bar{t}_{ij} w_j \qquad (3)$$

$$\text{WPM} = Z_i^{(2)} = \prod_{j=1}^{h} (\bar{t}_{ij})^{w_j} \qquad (4)$$

where $Z_i^{(1)}$ and $Z_i^{(2)}$ indicate the comparative significance of i^{th} option regarding the j^{th} attribute that is founded on the weighted sum and the weighted product approaches, correspondingly, while w_j represents the weightage of the attribute. Descriptions of calculations accounting for WSM and WPM for the $AlTiB_2$ composite analysis are presented in Table 3.

The results from Table 3 shows that Al-10%TiB_2 is the best alternative as it is having the maximum preference score value and therefore ranked 1. This can further be confirmed by the requirement of the composite having high strength and low ductility as can be seen in the decision criteria for Al-10%TiB_2. The entropy and critic methods are then employed in place of equal weight method and the summary of the weighted sum model is given using the general normalization in Table 4.

Table 3. Overall results using equal weigh, entropy and critic methods in WSM, WPM and WASPAS methods (min to max ratio method)

	Weighted sum method							
	Equal weight method		**Entropy method**		**CRITIC Method**		**Overall average**	
Description	**Preference score**	**Rank**	**Preference Score**	**Rank**	**Preference score**	**Rank**	**Preference score**	**Rank**
Al 6061 base alloy	0.7214	4	0.6176	4	0.7490	4	0.6960	4
Al-6% TiB_2	0.7994	3	0.7173	3	0.8200	3	0.7789	3
Al-8% TiB_2	0.8562	2	0.7943	2	0.8714	2	0.8406	2
Al-10% TiB_2	0.9999	1	1	1	1	1	0.9999	1
	Weighted product method							
Al 6061 base alloy	0.7087	4	0.6143	4	0.7371	4	0.6867	4
Al-6% TiB_2	0.7920	3	0.7089	3	0.8133	3	0.7714	3
Al-8% TiB_2	0.8522	2	0.7931	2	0.8677	2	0.8377	2
Al-10% TiB_2	1	1	1	1	1	1	1	1
	WASPAS method							
Al 6061 base alloy	0.7148	4	0.6165	4	0.7488	4	0.6934	4
Al-6% TiB_2	0.7957	3	0.7161	3	0.8202	3	0.7773	3
Al-8% TiB_2	0.8542	2	0.7935	2	0.8715	2	0.8597	2
Al-10% TiB_2	0.9999	1	0.9999	1	1	1	0.9997	1

Phase 4. Computation of the complete comparative importance for each option

According to Zavadskas et al. (2013a), Equation (5) is useful to compute the combined universal measure of weighted summative in additive and multiplicative approaches:

$$Z_i = 0.5Z_i^{(1)} + 0.5Z_i^{(2)} = 0.5\sum_{j=1}^{h}\bar{t}_{ij}w_j + 0.5\prod\nolimits_{j=1}^{h}(\bar{t}_{ij})^{w_j} \qquad (5)$$

More universal expression to establish the complete comparative importance if *the i*th option is computed on account of Equation (6) as indicated in Zavadska et al. (2012):

$$Z_i = \lambda Z_i^{(1)} + (1-\lambda)Z_i^{(1)} = \lambda\sum_{j=1}^{h}\bar{t}_{ij}w_j + (1\text{-}\lambda)\prod\nolimits_{j=1}^{h}(\bar{t}_{ij})^{w_j} \qquad (6)$$

Here λ is a factor of WASPAS approach. The outcome of λ occupies an array of 0 to 1. As λ =1, the WASPAS approach is similar in WSM characteristics and behaves similarly as WPS if λ = 0.

4. RESULTS AND DISCUSSION

The data used for the analysis of the multicriteria models were extracted from Christy's work (2010). Extracts of the ultimate tensile strength (UTS), ductility, and micro hardening data were made from the chapter on results and discussion. All three multicriteria models were tested on the data. The first multicriteria model used is the weighted sum model (WSM). Using the WSM to select the best alternative based on the criteria of ultimate tensile strength, ductility, and micro hardening, Table 1 is obtained. This Table 1 is simply the result of the decision matrix's normalization (step 1 of WSM). This analysis starts with the discussion of results from the WASPAS model implementation on establishing the best alternative among the fabricated composites, consisting of four options: Al-6061 base alloy, Al-6%TiB_2, Al-8%TiB_2, and Al-10%TiB_2. The equal weight method was used as the weighting factor in the computation of WASPAS results, and the following was the observation. The highest (score, 0.9999) performing material (Al-10%TiB_2, 1st rank) was identified, and the least (score, 0.7148) was assigned to Al-6061 base alloy (4th rank). The equal weight method implies that all the composite attributes (ultimate tensile strength, percentage ductility of the material, and the composite's micro hardening property) have identical weights. So, as there are three attributes, it is 33.33% each. This method has been criticized as incapable of outperforming the fundamental target, and as a result, this type of weight determination method is declared by researchers as not appropriate as a dependable analysis channel. There was no change in the highest score when the equal weight cum WASPAS results were compared with the overall average results. The overall average is when the following results were averaged: equal weight cum WASPAS, entropy weight cum WASPAS and CRITIC weight cum WASPAS. On the comparison, the score of the most preferred material for the overall average dropped by 0.02%. However, the least performing material dropped by 2.99%, indicating the degree of inaccuracy in the measurement offered by the equal weight method.

The entropy method is an objective technique for establishing the weights of the composite attributees of ultimate tensile strength, percentage ductility, and microhardness. The method employs decision matrix data and transforms it into a final value in which values indicate the proportions of the aforementioned attributes' importance in decimals whose sum is up to one. The entropy method is referred to in research to be close to what obtains in the real world. Some research work notes that the results of entropy weighing are close to those of data envelopment analysis. The entropy method was used to obtain weights in the WASPAS results from computation while the highest score (Al-10%TiB_2, 1st rank = 0.9999) was obtained and the lowest score (Al-6061 base alloy, 4th rank = 0.6165) was achieved. Compared with the method of overall average, the highest score (0.9997) is less than what the entropy yields (.i.e. 0.9999), indicating the computational rigour in the entropy method is evident in having higher variability value but the decision of Al-10%TiB_2 being the 1st rank is still being maintained. On the lower side, the 4th rank (Al-6061 base alloy) was the same in both entropy and overall average weight methods. However, by dimension, the entropy method (0.6165) has a lower score than the overall average (0.6934), indicating that the entropy method covers more variability than the overall average method.

The CRITIC technique is regarded as an objective approach to establishing the weights of criteria, notably the ultimate tensile strength, percentage ductility, and microhardness. The method was built up by Diakoulaki et al.'s initiative in 1995 and is based on the idea that the rigorousness of conflict within a constituent and the inappropriateness of each pair of constituents in a decision situation. The CRITIC weighing tool was used for weight determination of the WASPAS method, and the highest score (1st rank) was recognized as the Al-10%TiB_2 (1) while the least score was attained for Al-6061 base alloy (4th rank at 0.7488). Compared with the overall average, the highest score (1st rank, 0.9997) was still maintained as the same. However, the actual value of the score (obtained in CRITIC is higher than ($1_{\text{CRITIC}} > 0.9997_{\text{overall average}}$) that was attained for the overall average, suggesting that the overall average covers less of the variability of the class than the CRITIC results. On the lower side, although the same decision on the result (0.7488_{CRITIC}, 4th rank = $0.6934_{\text{overall average}}$, 4th rank) was obtained for both the CRITIC method and the overall average used to compute the WASPAS method results, the variability was more in the overall result than in the CRITIC method. This may be because CRITIC has a more thorough computational approach than the overall average, a mixture of computational approaches of three main methods whose average was sought for.

In the preceding discussion, the composite specimens' scores for each of the three weight determination methods (equal weight, entropy, and CRITIC) were established, and each composite was placed against a rank based on these scores. Interestingly, any of these methods could have been adopted. To understand the relationship between any pair of weight determination results, this article introduces the coefficient of determination, R^2, to specifically reveal the extent (very strong, strong, weak, very weak) of the association between pairs, such as equal weight versus entropy, equal weight versus CRITIC, equal weight versus overall average, entropy versus overall average and CRITIC versus overall average. This is to state the level of confidence any two methods of weight determination could be used. The value of R, coefficient of correlation, is often squared to obtain the coefficient of determination, specified between 0 and 1. Statistics has become a useful tool to achieve this decision. In this article, the coefficient of determination (R^2) has been calculated (Table 4), and comments on pairs of methods are discussed.

In comparing the entropy method and equal weight, the R^2 yielded 0.9994, indicating that there is a strong relationship between these two methods, and either can serve the purpose of analyzing the evaluation scheme. On comparing the R^2 between equal weight and CRITIC method as inputs to the WASPAS technique, a value of 1 was obtained, showing a very strong relationship between the two. The same comments to the other paired methods equally apply here. For the relationship between the equal weight and the overall average, a value of $R^2 = 0.9977$ was obtained, indicating an interesting relationship in which the equal weight method is positively related with the overall average method. An effort to test the R^2 between the entropy method and the overall average to yield the results of WASPAS indicates a high value of 0.9958, which shows an acceptable coefficient of determination. On comparing the CRITIC method and the overall average method used on the WASPAS model, the result was an R^2 of 0.9977, showing a powerful relationship between the two methods. In summary, five pairs of tests were conducted and all the tests yielded very strong scores of the coefficient of determination, indicating that all the models developed are capable of evaluating the composite specimens under the selection process. This can be further confirmed by the requirement of the composite having high strength and low ductility, as can be observed in the decision criterion for Al-10%TiB_2.

Tables 5 and Table 6 reveal the ranks of the attributes and the summarized form of ranking in a frequency perspective. From Table 6, the specimen option Al-10%TiB_2 has 100% occurrence as the first position, and this concurs with Christy's (2010) choice. The outcome achieved from the WASPAS technique diverges with the departure in the WASPAS lambda parameter, λ, which fluctuated from 0 to 1 for each weight determination method. Table 5 shows the result from the equal weight determination method used to compute the WASPAS model for various ranges of λ. As $\lambda = 0$, the option Al-10%TiB_2 obtains the utmost WASPAS score

(0.8517) and acquires the first rank, which signifies it as the highest desirable specimen in terms of tensile strength (ultimate tensile strength and percentage ductility) and metallurgical property of microhardness among all. The Al-6061 base alloy attains 0.8317 WASPAS score and achieves the 4th order that denotes it as the least in the content of the desired tensile and metallurgical properties. As the λ attains 0.5, the Al-10%TiB_2 specimen (WASPAS score = 0.8411) options embrace the first and fourth-order concurrently.

As the value of λ =1, the Al-10%TiB_2 specimen (WASPAS score =0.8630) option again grasps the first order, and the Al-8%TiB_2 specimen (WASPAS score = 0.8443) option attains the fourth-order. It reveals that Al-10%TiB_2 is a largely enriched specimen with the desired tensile and metallurgical properties. In contrast, the Al-8%TiB_2 specimen is the least enriched specimen regarding the desired tensile and metallurgical properties in the composite choice as the TiB_2 metal is welded to the matrix Al-6061 base alloy. The utmost WASPAS score symbolizes the pinnacle priority option, while the least score reveals the least priority option. The pinnacle priority option arising from the WASPAS outcome is Al-10%TiB_2 in all situations as the value λ ranges from 0 to 1.

Table 4. Coefficient of determination (R^2) for pairs of weight evaluation methods

Equal weight vs entropy		**Equal weight vs CRITIC**		**Equal weight vs overall average**		**Entropy vs overall average**		**CRITIC vs overall average**	
Value	Comment	Value	Comment	Value	Comment	Value	Comment	Value	Comment
0.9988	Very strong	1	Very strong	0.9977	Very strong	0.9958	Very strong	0.9977	Very strong

Table 5. Ranking of Al-6061 base alloy and Al-TiB_2 composites using WASPAS (weight determination method: Equal weights of criteria)

	Comparative importance Z_i and ranks of options							
	Al-6061 base alloy		**Al-6%TiB_2**		**Al-8%TiB_2**		**Al-10%TiB_2**	
λ	Z_1	**Rank**	Z_2	**Rank**	Z_3	**Rank**	Z_4	**Rank**
0	0.8317	4	0.8369	3	0.8417	2	0.8517	1
0.1	0.8344	4	0.8378	3	0.8420	2	0.8528	1
0.2	0.8371	4	0.8386	3	0.8422	2	0.8540	1
0.3	0.8397	3	0.8394	4	0.8425	2	0.8551	1
0.4	0.8424	3	0.8402	4	0.8427	2	0.8562	1
0.5	0.8451	2	0.8411	4	0.8430	3	0.8574	1
0.6	0.8477	2	0.8419	4	0.8433	3	0.8585	1
0.7	0.8504	2	0.8427	4	0.8435	3	0.8596	1
0.8	0.8530	2	0.8435	4	0.8438	3	0.8608	1
0.9	0.8557	2	0.8444	3	0.8441	4	0.8619	1
1.0	0.8584	2	0.8452	3	0.8443	4	0.8630	1

Table 6. Summary of cases (percentages) where the attributes take in positions while ranking with WASPAS (equal weight method)

Descriptions	Al-6061 base alloy	Al-6%TiB_2	Al-8%TiB_2	Al-10%TiB_2
No of cases as 1st ranked	-	-	-	100
No of cases as 2nd ranked	54.55	-	45.45	-
No of cases as 3rd ranked	18.18	45.45	36.36	-
No of cases as 4th ranked	27.27	54.55	18.18	-
Overall assessment	3rd ranked	4th ranked	2nd ranked	1st ranked

For the WASPAS technique, the precedence of the options follows as:
$\lambda = 0$: Al-10%TiB_2 > Al-8%TiB_2 > Al-6%TiB_2 > Al-6061 base alloy
$\lambda = 0.1$: Al-10%TiB_2 > Al-8%TiB_2 > Al-6%TiB_2 > Al-6061 base alloy
$\lambda = 0.2$: Al-10%TiB_2 > Al-8%TiB_2 > Al-6%TiB_2 > Al-6061 base alloy
$\lambda = 0.3$: Al-10%TiB_2 > Al-8%TiB_2 > Al-6061 base alloy > Al-6%TiB_2
$\lambda = 0.4$: Al-10%TiB_2 > Al-8%TiB_2 > Al-6061 base alloy > Al-6%TiB_2
$\lambda = 0.5$: Al-10%TiB_2 > Al-6061 base alloy > Al-8%TiB_2 > Al-6%TiB_2
$\lambda = 0.6$: Al-10%TiB_2 > Al-6061 base alloy > Al-8%TiB_2 > Al-6%TiB_2
$\lambda = 0.7$: Al-10%TiB_2 > Al-6061 base alloy > Al-8%TiB_2 > Al-6%TiB_2
$\lambda = 0.8$: Al-10%TiB_2 > Al-6061 base alloy > Al-8%TiB_2 > Al-6%TiB_2
$\lambda = 0.9$: Al-10%TiB_2 > Al-6061 base alloy > Al-6%TiB_2 > Al-8%TiB_2
$\lambda = 1$: Al-10%TiB_2 > Al-6061 base alloy > Al-6%TiB_2 > Al-8%TiB_2

Consistent with the outcome of WASPAS technique, the Al-10%TiB_2 option achieved the first order amongst the options in every case of WASPAS parameter, $\lambda = 0$ to $\lambda = 1$. The expert allocates more weight to the Al-10%TiB_2 option since it satisfies the challenge of tensile strength and metallurgical characteristics enrichment and certainly, it tends to be the leading issue as Al-6%TiB_2 is rising as relatively less attractive in all cases.

The selection process is a compulsory task for the composite developer during the preliminary experiments. In this process, the composite designer obtains responses from different prepared composites to channel efforts and resources to the specimen that yields the most satisfactory response. In the current situation, tensile and microstructural tests yielded the needed responses from the composites in terms of the ultimate tensile strength, percentage ductility, and the samples' microhardness. Without a clear understanding of the preliminary test results, investing energy and time in further processing, the materials will involve a lot of waste in materials and manhours in fabrication. So, objective selection is encouraged. Knowledge from the tests and selection process is transferable from a fabrication organization to others within the sector. The WASPAS technique has been proposed in this work due to its robust structure; reliability, and ranking accuracy. Outputs from the selection process using WASPAS may be used in the product design process, and the cost of the new product may be estimated. However, further efforts on the composite development process may be a waste without a clear and convincing selection procedure.

4.1. Contributions to knowledge on friction stir welding

This article is a unique contribution, which saturates the gap of WASPAS model for a valuable application in the perspective of friction stir composite welding process, chiefly in Al-TiB_2 composite development. The fabrication industry may employ the model as a problem-solving tool to weigh a product against the other. In using the model to check the superiority of a composite specimen over the other, the composite designer could ascertain which product he/she should be biased toward, which gives the highest weight. As the right choice of product is made, an enhancement drive could be pursued to upgrade them to the desired standards.

This is the pioneering use and validation of the WASPAS model using Christy's (2010) data on real experimental conduct. The outcome reveals the value and use of the WASPAS model. Through this WASPAS model, the fabricator can appreciate the importance of expert knowledge to attain the most effective choice of Al-TiB_2 composite. This understanding may motivate the composite developer to actualize planned decisions to create better product choices for the composite company. Secondly, this research contributes to the lack of quantitative models researching the procedure to adopt in choosing the best product from a class of Al-TiB_2 composites of varying TiB_2 compositions. This is meant to improve the understanding of the principle of selection in the actual world scenario.

To summarise this article's contributions, it was found that the innovative strategy of friction stir welding could be used to produce Al-TiB2 composites with the alloying element, TiB_2, producing various products containing 6-10%TiB_2 reinforcements. Furthermore, the composite developer is supported by intuition and experience to choose the best option as proposed in previous research. However, the need to eliminate bias and sub-optimal decisions motivate the search for robust research to adopt objective multicriteria approaches based on the WASPAS theory somewhat different from the idea reported in previous composite selection research. Further, the WASPAS theory emerges as a reliable multicriteria tool not established in previous research on Al-TiB_2 composite development and selection. Also, the performance of the WASPAS model was validated with experimental data reported in previous literature. Finally, the analysis from the article supports the idea about friction stir welded Al-TiB_2 composite as robustly influenced by WASPAS multicriteria model in the choice of the preferred composite class.

4.2. The novelty of the study

Previous research has approached the selection of the best Al-TiB_2 composite in the welding of Al-60661 base alloy with various fractions of Al-TiB_2 in a friction stir welding environment. This research has typically revealed that such selection is at best done at the experience and intuition practice of the experimental personnel. In contrast, the present study is the first effort to select the best Al-TiB_2 composite using an objective approach. The WASPAS multicriteria method based on the outstanding ranking accuracy and the elevated reliability of the results yields. It was shown that using three methods of equal weights, entropy and CRITIC to determine the weights of the criteria as inputs to the WASPAS multicriteria technique, the complication involved in the selection process was made easy and feasible to calculate results. In its wide range of testing using different weight determination, the method justified the superiority of Al-10%TiB_2 composite as being ranked as the first specimen. This concurs with intuition practice, and the consistency in the choice of Al-10%TiB_2 composite as the supreme first-rate choice is the unique property of the model. WASPAS method has been proved a robust multicriteria model in choosing the best composite and a useful guide in composite development, design, and planning.

4.3. Selection research impact on organization and society

The WASPAS multicriteria tool is one of the most recently developed selection tools, with the foundation in operations research. It motivates researchers and practitioners to view selections in a new way. The use of the weighted sum model and weighted product model are two ways of previously viewing the selection process. However, with innovative WASPAS, researchers and practitioners are more at the advantage of making more robust decisions. This paper introduces a new learning paradigm that will add to the enhancement of the organization and society. Engineers in the society will be tackling several projects in their careers, striving to meet deadlines on challenging tasks with time constraints and pressure to add value to the system. In this work, the selection of the best composite during the fabrication and welding of a range of composites is specified. In society, similar concepts prevail, and this new learning can be transferred to this new situation. By implementing the method described in this work, cost-effective and sustainable practices are encouraged.

Furthermore, this paper details how the innovative WASPAS may effectively drive the welding resource conservation effort in engineering and the conservative practices in society. The preference scores and ranks of the criteria are revealed as the principal driving forces of decisions. It may influence the attitudinal viewpoint of process engineers who engage in friction stir welding for resource conservation. It drives through the selection and channeling of resources to each parameter's needs in the friction welding process. This influences employees' relationships. Previously, welders compete for resources that are distributed based on trial and error. In a manner, the result disclosed in the study promotes effective business strategy decisions. It provides helpful technical information on the welding process to the general manager of the organization.

5. CONCLUSION

After examining the results, the study concluded that the result of WSM, the Al-10%TB_2 is the best alternative as it has the maximum preference score value and therefore ranked first. The worst-ranked criterion is Al6061 based alloy. This occurred for all the input categories of equal weight method, entropy method, and the CRITIC method. This can be further confirmed by the composite's requirement having high strength and low ductility, as can be observed in the decision criterion for Al-10%TiB_2. The composite Al-10%TiB_2 composite also emerged as the best composite based on all the three multicriteria methods of weighted sum method, weighted product method, and WASPAS. However, the worst criterion was known to be the Al6061 base alloy in all the methods.

Overall, the Al-10%TiB_2 is considered the best option, while the Al6061 based alloy is taken as the worst material by ranking. It is possible to have different results if the following normalization techniques are linear (max-min), linear (sum), vector normalization, and logarithmic normalization. Consequently, future investigators could examine the mentioned normalization methods. It may also be interesting to consider utilizing the weight determination techniques of equal weights, CRITIC, and entropy as a level. Simultaneously, Taguchi, Taguchi-Pareto, and Taguchi-ABC optimization methods are applied to the model for possible results. This work advances knowledge on selecting the best composites during fabrication as it tackles how the material properties may be normalized and eventually used to determine the preference scores of the multicriteria methods. As such, logical evidence is offered to establish the composite options that are ideal candidates for further investment of commercial production resources. Besides, fabricators could use the research for production planning and estimation goals.

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