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Research Note

Multi response optimization of friction stir welding in air and water by analytic hierarchy process and VIKOR method

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Abstract. Friction Stir Welding (FSW) of titanium sheets was carried out under air and water environment, and the tensile properties of the joints made were measured. The tool rotational speed and tool traversing speed, which significantly influence the tensile properties of the welded joints, were considered as input process parameters. This work deals with the application of the analytic hierarchy process to calculate the weights of the relative importance of the output responses using a pairwise comparison of responses and checks for the consistency and acceptability of the assumed comparison. Also, the Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) optimization technique, a multi-response multi-criterion method, was used to determine the optimum process parameters. From the VIKOR optimization method, it is observed that the higher tool rotational speed and lower tool traversing speed are the optimum process parameters in both conventional and underwater FSW. The results from the experimental measurements and the study of microstructure support the results obtained from the VIKOR optimization method.

1. Introduction

Friction Stir Welding (FSW) is an eco-friendly solid-state welding process due to the absence of fumes and arcs, which are common in conventional welding processes [1]. Attempts have been made to perform underwater FSW (UFSW), also referred to as Submerged FSW (SFSW), to explore the possible applications under environments different from that of air [2]. Generally, the process parameters used in the FSW process are tool rotational speed, feed, tool pin shape, pin size, shoulder size, and tilt angle of the tool. These parameters were optimized to attain the improvement in different mechanical properties. Ghiasvand et al. [3] performed a novel method known as parallel FSW,

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and the resulting mechanical properties were compared with that of conventional FSW. It was concluded that there is a significant improvement in the mechanical properties of the welded joints made by parallel FSW over the conventional method. Lombard et al. [4] tried to optimize the process parameters in order to achieve a weldment with higher fatigue life and negligible defects in aluminum alloy AA5083-H321. The mechanical properties of the joint made by FSW in AM60 and AZ31 magnesium alloys were optimized by Zhang et al. [5] by considering the tool rotational speed. Similar work was carried out by Sevvel and Jaiganesh [6] using AZ31B, taking the effect of tool rotational speed and feed on the output results. Four different shapes of the tool pin, such as triangle, frustum, hexagonal, and cubic, were used to study their influence on the mechanical and microstructural properties of the aluminum-steel welded joints made in UFSW. From the investigation, it was presented that the internal material flow is better in a pin having a greater number of edges and the descending order in which the generation of frictional heat is hexagonal, cubic, triangle, and frustum pin shape [7]. UFSW of the same combination of metals under different cooling atmospheres like Low-Temperature Water (LTW), Room-Temperature Water (RTW), High-Temperature Water (HTW), and air was investigated by Derazkola and Khodabakhshi [8].

It was concluded that excellent results were observed in tensile strength and elongation at RTW cooling atmosphere, whereas the higher and lower cooling rate reduced the transverse tensile properties and also noticed the reduced formation of Intermetallic Compound (IMC) when the cooling medium temperature is decreased. The thermal and material flow analysis of UFSW of aluminum-magnesium alloy using the computational fluid dynamic (CFD) has revealed that the maximum heat generated in FSW is 7% more than the UFSW and the increased cooling due to the surrounding water reduced the flow rate of heat [9].

Researchers have attempted to develop a mathematical model for the output responses and optimized the process parameters by response surface graphs [10,11]. Also, successful optimization of FSW of dissimilar aluminum alloys [12], ferritic steels [13], and stainless steel AISI 316L [14] was carried out using Response Surface Methodology (RSM). Different approaches have been made in the past by researchers to optimize the process parameters, such as the Taguchi method [15], modeling and testing with Analysis of Variance (ANOVA) [16], RSM in conjunction with Central Composite Design (CCD) [17], and Taguchi-ANOVA-RSM [18]. The optimization of the FSW process was performed by analyzing the heat transfer using the sequential quadratic programming gradient (SQP) algorithm coupled with CFD code for the thermal model [19]. Artificial Neural Networks (ANN) are one of the techniques for developing predictive models and are able to solve the problems where uncertainty and nonlinearity are at higher levels [20]. Mohammadzadeh Jamalian et al. [21] used ANN to choose the best profile of the pin so as to maximize the ultimate tensile strength of the friction stir welded joints. To investigate the influence of the process parameters on the tensile properties of the welds made in copper material, Heidarzadeh et al. employed fuzzy logic-based models [22]. Optimization of the process parameters was carried out by a hybrid method, which comprises Taguchi-Grey Relation Analysis (GRA)-ANN by Wakchaure et al. [23] to attain the optimum mechanical properties. Shehabeldeen et al. [24] developed a predictive model for mapping the input and output parameters using an Adaptive Neuro-Fuzzy Inference System (ANFIS), which is an integration of ANN and fuzzy logic, and optimized the parameters by Harris Hawks Optimizer (HHO). Banik et al. [25] presented a multi-objective hybrid optimization method utilizing Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Principal Component Analysis (PCA). Hybrid Differential Evolution (DE) and Particle Swarm Optimization (PSO) approach were applied by Caseiro et al. [26] to find out the optimal configuration of Integrally Stiffened Panels (ISP) joined by FSW and proved that the hybrid method is more effective than the other optimization techniques. Pitchipoo et al. [27] proposed a Dragon Fly algorithm (DFA) optimization, a technique that is better than the other optimizing methods due to its efficiency, speed of convergence, etc., to optimize the input parameters so as to achieve an optimal tensile strength of the welds.

The Analytic Hierarchy Process (AHP) is one of the Multi-Criteria Decision-Making (MCDM) methods in which the problem under consideration is broken into a hierarchy of interrelated elements and provides a comprehensive structure during the process of decision-making. The AHP has the following advantages: (i) flexibility; (ii) easy to handle; (iii) capable of indicating the measures of consistency in judgment made, and (iv) takes into account tangible and intangible factors [28]. The AHP uses a pairwise comparison, at all levels, of the hierarchy of elements and finds out the preferences of the set criteria [29].

Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR), which means multi-criteria optimization and compromise solution, is one of the popular MCDM tools to solve problems with conflicting factors. Tong et al. compared the conventional Taguchi method and the VIKOR method of optimization. The study has revealed the following conclusions: (i) Taguchi SN ratio takes into account the mean and variance of a characteristic of the quality and can be used

Table 1. FSW parameters used in air and water.

No.	Process parameters	Values
1	Tool rotational speed	400;500 rpm
2	Tool traversing speed	80;100;120;140;160 mm/min

for a single response optimization process effectively and (ii) the VIKOR method takes into account the measure of utility and regret and is very much effective in multi-response optimization [30]. The VIKOR optimization technique is considered to be a simple, effective, and suitable method for optimizing the process parameters of any type of welding process. Due to these advantages, Aravind et al. [31] executed the VIKOR optimization method to optimize the parameters used for cold metal transfer welding for achieving the set criteria for the size of the reinforcement, penetration depth, width of the weld bead, and width of the heat affected zone in Al5083 aluminum alloy welded joints. To optimize the width of the bead, penetration depth, and microhardness of the laser welded joints of titanium Ti6AL4V sheets, Aravind et al. employed the VIKOR method and verified it with experimental results [32]. Also, the VIKOR optimization is adopted for the comprehensive analysis and evaluation in different fields such as crashworthiness performance in trains [33], electrical discharge machining process parameter optimization [34], material selection for thermal energy storage systems [35], ecological security of water [36] and selection of vaccine for COVID-19 [37].

Different optimization techniques were performed in FSW in the past. From the review of the literature, it is observed that most of the researchers used these techniques to optimize either the single response or multi-responses individually in FSW carried out in the air. However, there is a gap in optimizing the multi-responses in FSW performed underwater, and also, there is no comparison made between optimized parameters obtained in air and water FSW. Also, the VIKOR optimization method is one of the simple and efficient techniques to identify the optimum process parameters in multi-objective functions. To fill this gap, multi-response optimization is carried out using AHP and VIKOR methods to optimize the process parameters used in conventional FSW and UFSW to achieve the optimum tensile properties. The results obtained may open a new process window to achieve good welded joints in titanium sheets by FSW performed in air and water.

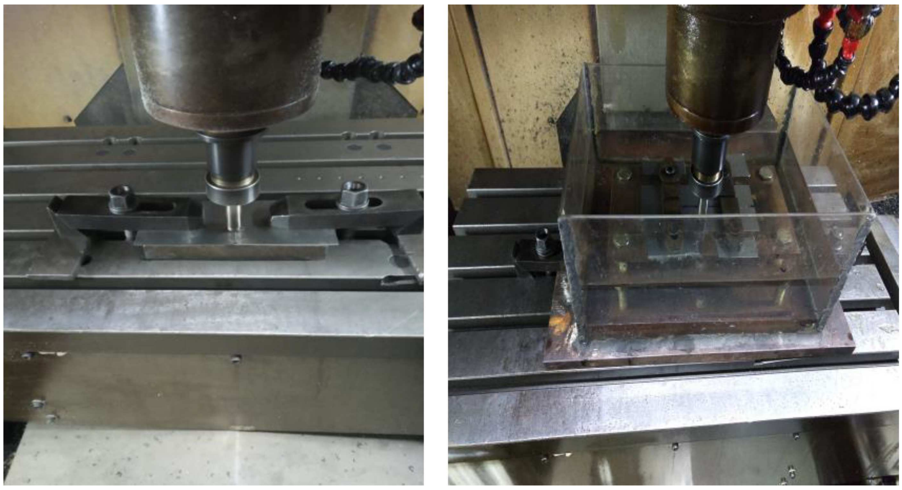
2. Materials and methods

Experimentation: The FSW experiments were conducted using a 1 mm thick titanium grade 1 sheet in air and water. Due to the lack of availability of literature on FSW of 1 mm titanium sheet in air and water, the selection of the process window was a challenge. The following initial range of process parameters are fixed based on the literature on the FSW of other materials: Tool rotational speed range = 100–1000 rpm and tool traveling speed range = 40–200 mm/min. Trial and error experimentations within this range narrowed down the process parameters selection to rotational speeds of 400 and 500 rpm and 80–160 mm/min. Low rotational speed below 400 rpm and high traveling speed above 160 mm/min produced incomplete welding due to the poor heat generation in both air and water. In both FSWs, higher rotational speed above 500 rpm and below 80 mm/min produced overheating in the stir region, burnt the sheet material and also damaged the tool. The various process parameters used in these experiments are presented in Table 1.

High Carbon High Chromium (HCHCr) is the tool material used. The shape of the pin in the stirring tool is cylindrical, with a pin diameter of 10 mm and a pin length of 0.8 mm. The shoulder diameter of the tool is 16 mm, and the overall length is 120 mm. The FSW in the air was performed by fixing the plates on the machine bed with a backup plate. A specially designed container with a fixture was used for the UFSW process. The water is stagnant, and the initial temperature of water in the container is 25°C. The FSW tool used for air and water is presented in Figure 1, and the welding setup for air and water is shown in Figure 2.

The operation was carried out in CNC vertical machining center (LITZ MV-800) which is shown in Figure 3. Ten experiments are carried out in air and ten experiments in water, respectively, based on the L9 orthogonal array from the Taguchi method, with one additional experiment. The output responses Yield Strength (YS), Tensile Strength (TS), and % Elongation were measured using tensile testing of the

Figure 1. Tool used for FSW in air and water.



(a) FSW in air

(b) FSW in water

Figure 2. Welding setup.

Figure 3. CNC vertical machining center.

Figure 4. Specimen for tensile testing.

welded joints according to the ASTME-E8 standard. The tensile specimen is shown in Figure 4.

2.1. Analytic Hierarchy Process (AHP)

AHP is used to find the weights of the relative importance of the factors used. It decides the preferences among the criteria that are set using pairwise comparisons. The quality of importance of the factors, according to Saaty (1980), is presented in Table 2. The matrix A, using the comparison, will be formed where a_{ij} is the element of the matrix obtained by comparing A_i of the ith row with the A_j of the jth column. The pairwise comparison is shown in Table 3.

Table 2. Quality of significance of the factors [32].

Description	Quality level of significance
Intermediate values	2,4,6,8
Absolute	9
Very much strong	7
Essential/strong	5
Moderate	3
Equal importance	1

Table 3. Pairwise comparison.

Output responses	YS	TS	%EL
Yield Strength (YS)	1	7	3
Tensile Strength (TS)	1/7	1	1/5
% Elongation (% EL)	1/3	5	1

In Table 3, the value 1 indicates equal importance, and the value 7 indicates the YS is 7 times more important than the TS. Hence, the TS is 1/7 times less important than the YS.

Therefore:

$$A=\begin{pmatrix} 1 & 7 & 3 \\ 0.1428 & 1 & 0.2 \\ 0.333 & 5 & 1 \end{pmatrix}.$$

The weightage is calculated using the Eqs. (1) and (2) from [32]. For a given ith row:

$$\mathrm{GM}_i=\left\{\prod_{j=1}^{b} a_{ij}\right\}^{1/b}, \tag{1}$$

$$W_j=\frac{GM_i}{\sum\limits_{i=1}^{N} GM_i}, \tag{2}$$

Table 4. Random Consistency Index (RI).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

where a_{ij} is the element in the ith row and the jth column of matrix A.

In order to check the consistency of comparison made among the responses shown in Table 3, the following procedure is adopted.

First, the weighted sum of the responses and the eigenvalue (λ) is calculated for each row based on the given Eq. (3). For a given i:

$$\lambda_i = \frac{\sum_{j=1}^{b} W_j x_{ij}}{W_i}. \tag{3}$$

Then, the maximum eigenvalue ($\lambda_{\max}$) is calculated using Eq. (4):

$$\lambda_{\max} = \frac{\sum_{i=1}^{a} \lambda_i}{a}. \tag{4}$$

According to Satty (1977), a Consistency Index (CI) can be calculated using formula (5):

$$CI = \frac{\lambda_{\max} - n}{n-1}, \tag{5}$$

where n is the order of the matrix.

The calculated CI value is compared with the appropriate consistency index, known as the Random Consistency Index (RI). The RI values are taken from the Table 4 (Satty, 1980). The comparison between the CI and RI, known as Consistency Ratio (CR), is calculated using the formula shown in Eq. (6):

$$CR = \frac{CI}{RI}. \tag{6}$$

If the calculated CR value is less than 10% (0.1), the pairwise comparison matrix (A) formed is consistent and acceptable. The pairwise comparison matrix is not consistent and reliable when the CR value is more than 10%, and the pairwise comparison values need to be altered to achieve consistency.

2.2. VIKOR optimization method

To identify the optimum process parameters, the VIKOR optimization method is used, which is one of the MCDM techniques. The procedure includes the calculation of the utility factor and regret factor from which the VIKOR index is determined. Then, the ranking is done based on the ascending values of the VIKOR index, and the optimal solution is derived from the smallest VIKOR index. The following steps are employed in VIKOR optimization:

- **Step 1.** Determination of Normalized decision matrix.

Let X be the decision matrix formed with the values of output responses under consideration. Then, the elements p_{ij} of the normalized decision matrix P [32] can be calculated from the decision matrix X using the Eqs. (7) and (8):

$$p_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{a} {x_{ij}}^2}}, \tag{7}$$

and:

$$P = [p_{ij}]_{a \times b}, \tag{8}$$

where $i = 1, 2, 3, ..., a$ and $j = 1, 2, 3, ..., b$.

- **Step 2.** Determination of the weightages of the comparative significance of the factors.

The weightages are calculated, and the pairwise comparison values made are checked for their consistency and acceptability using the AHP procedure explained in the previous section.

- **Step 3.** Calculation of utility factor (S_i) and regret factor (R_i).

The selection of the optimal parameters is based on the criteria that the welded joints must have higher YS and TS, whereas the %EL must be lower.

The following Eqs. (9)–(12) are used for calculation.

For maximum criteria:

$$S_i = \sum_{j=1}^{b} W_j \frac{(p_{j\max} - p_{ij})}{(p_{\max} - p_{j\min})}, \tag{9}$$

$$\mathrm{R}_i = \max_i \left[W_j \frac{(p_{j\max} - p_{ij})}{(p_{\max} - p_{j\min})} \right]. \tag{10}$$

For minimum criteria:

$$S_i = \sum_{j=1}^{b} W_j \frac{(p_{ij} - p_{j\min})}{(p_{\max} - p_{j\min})}, \tag{11}$$

$$R_i = \max_i \left[W_j \tfrac{(p_{ij} - p_{j\min})}{(p_{\max} - p_{j\min})} \right]. \tag{12}$$

- **Step 4.** Determination of VIKOR constant.

Using Eq. (13), the VIKOR constant can be calculated:

$$Q_i = V * \left[\frac{S_i - S_{\min}}{S_{\max} - S_{\min}} \right] + (1 - V) * \left[\frac{R_i - R_{\min}}{R_{\max} - R_{\min}} \right], \tag{13}$$

where, $i = 1, 2, 3..., a$.

V, a constant, is the weight incorporated to keep up the plan of action of maximum group utility, and its value ranges from 0 to 1; but, in general, the value is considered to be 0.5.

- **Step 5.** Ranking of alternatives.

  Based on the calculated Q_i values, the alternatives are ranked in ascending order.

- **Step 6.** Proposing the optimal solution.

  The optimal parameters for the best responses correspond to the lowest value of the VIKOR constant.

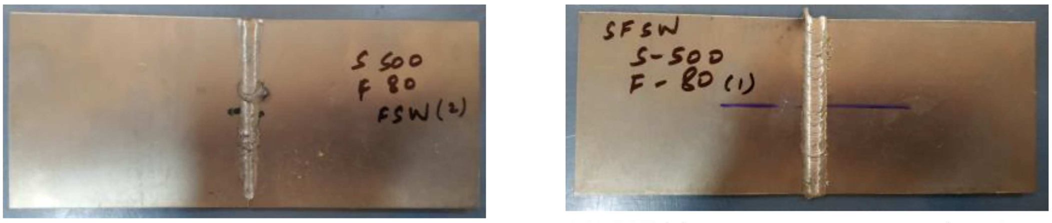
3. Results and discussion

The FSW was carried out using the Ti sheets in an air and water environment, and the joints were tested for the output responses such as YS, TS, and %EL, which are tabulated in Table 5. The welded samples made in air and water at different process parameters are shown in Figure 5.

The value 0 indicates that the welded joints are broken by hand force or gripping in the tensile testing machine. The calculated weightage of the output responses using the Eqs. (1) and (2) are presented in Table 6.

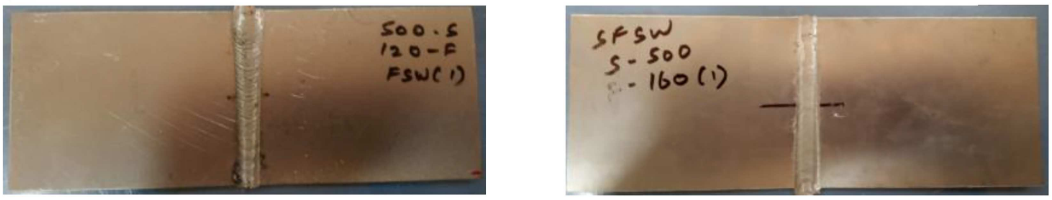
Table 5. Output responses.

No.	Speed (rpm)	Feed (mm/min)	Air			Water		
			YS (MPa)	TS (MPa)	%EL	YS (MPa)	TS (MPa)	%EL
1	400	80	220	246	0.5	292	437	1
2	400	100	188	204	1	274	362	1
3	400	120	66	71	2	193	244	1
4	400	140	0	0	0	184	240	2
5	400	160	0	0	0	29	32	5
6	500	80	267	308	0.5	317	456	1
7	500	100	203	227	1	251	339	1
8	500	120	59	67	2	246	320	1
9	500	140	0	0	0	216	260	2
10	500	160	0	0	0	177	219	2.5



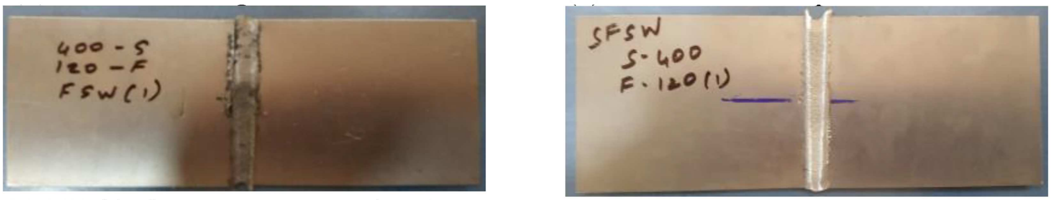
(a) FSW at 500 rpm 80 mm/min

(d) UFSW at 500 rpm 80 mm/min



(b) FSW at 500 rpm 120 mm/min

(e) UFSW at 500 rpm 160 mm/min



(c) FSW at 400 rpm 120 mm/min

(f) UFSW at 400 rpm 120 mm/min

Figure 5. Welded joints at different process parameters.

Table 6. Weightage of the output responses using AHP.

Output ersponses	YS	TS	%EL	Product of the values	GM_i	Weightage W_j
YS	1	7	3	21	2.758924	**0.649**
TS	0.1428	1	0.2	0.0286	0.30567	**0.072**
%EL	0.333	5	1	1.6650	1.185236	**0.279**

Table 7. Calculation for checking the consistency.

Output responses	YS	TS	%EL	Weightage W_j	λ	$\lambda_{\max}$ = Mean of λ
YS	1	7	3	0.649	3.066	**3.066**
TS	0.1428	1	0.2	0.072	3.069	
%EL	0.333	5	1	0.279	3.064	

Table 8. Normalized decision matrix.

	Air			Water		
No.	**YS**	**TS**	**%EL**	**YS**	**TS**	**%EL**
1	0.486994	0.48426	0.154303	0.399484	0.441214	0.148659
2	0.416158	0.401582	0.308607	0.374858	0.36549	0.148659
3	0.146098	0.139766	0.617213	0.264043	0.246353	0.148659
4	0	0	0	0.25173	0.242314	0.297318
5	0	0	0	0.039675	0.032309	0.743294
6	0.591034	0.60631	0.154303	0.433687	0.460397	0.148659
7	0.449363	0.446858	0.308607	0.343392	0.342269	0.148659
8	0.130603	0.131892	0.617213	0.336552	0.323085	0.148659
9	0	0	0	0.295509	0.262507	0.297318
10	0	0	0	0.242153	0.221112	0.317647

Table 9. Calculated S_i, R_i, Q_i, and corresponding ranking.

	Air				Water			
No.	S_i	R_i	Q_i	**Rank**	S_i	R_i	Q_i	**Rank**
1	0.198487	0.114243	0.121874	2	0.059563	0.056337	0.073184	2
2	0.355838	0.192026	0.291032	4	0.112862	0.096899	0.131083	3
3	0.822976	0.488573	0.849884	5	0.315431	0.279431	0.372993	7
4	0.721000	0.649000	0.922244	7	0.406141	0.299711	0.433973	8
5	0.721000	0.649000	0.922244	7	1	0.649000	1	10
6	0.069750	0.069750	0	1	0	0	0	1
7	0.314001	0.155566	0.232437	3	0.168597	0.148729	0.198882	4
8	0.840926	0.505588	0.876209	6	0.183091	0.159997	0.214809	5
9	0.721000	0.649000	0.922244	7	0.330634	0.227600	0.340664	6
10	0.721000	0.649000	0.922244	7	0.460356	0.315486	0.473134	9

To check the consistency of the pairwise comparison, the following calculations (Table 7) are made:

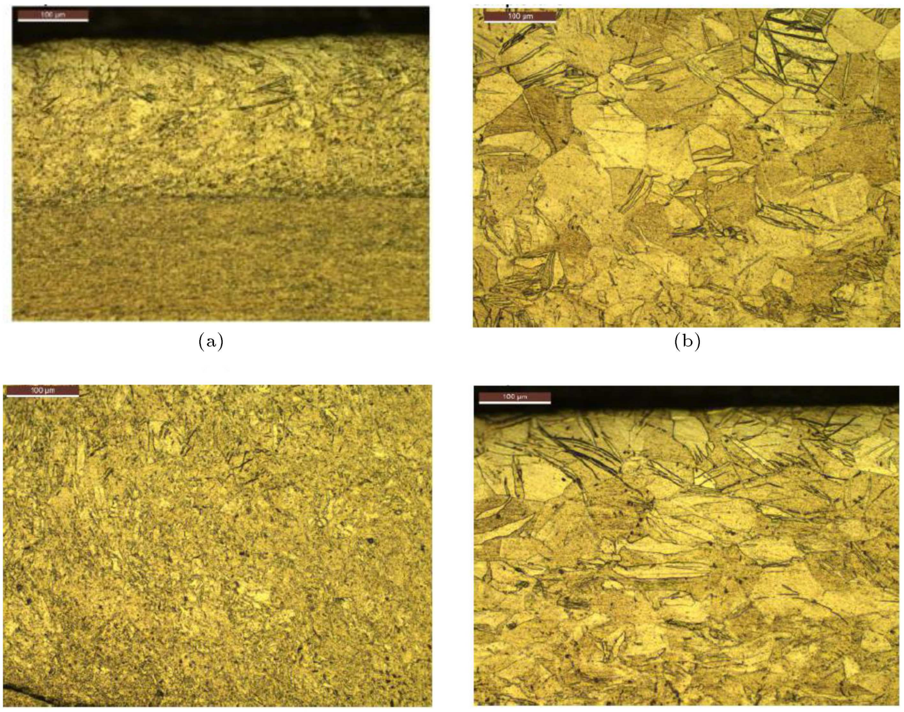
$$CI = \frac{(3.066 - 3)}{2} = 0.033, \quad \text{from Table 4,}$$

$$RI = 0.58, \quad \text{for } n = 3, \quad CR = \frac{0.58}{0.033} = 0.0568.$$

Since $CR < 0.1$, the weightage, and hence, the pairwise comparison are reliable and acceptable.

The normalized decision matrix of the output responses for both conventional FSW and UFSW is provided in Table 8. The calculated Utility factor (S_i), Regret factor (R_i), VIKOR constant (Q_i), and the corresponding ranking for both air and water FSW are shown in Table 9.

The tool rotational speed of 500 rpm and tool traversing speed of 80 mm/min are the optimal process parameters observed from Table 9 in the case of both



(a) (b)

(c) (d)

Figure 6. Microstructure of the welded joints: (a) FSW at 500 rpm 80 mm/min; (b) FSW at 400 rpm 120 mm/min; (c) UFSW at 500 rpm 80 mm/min; and (d) UFSW at 500 rpm 140 mm/min.

conventional FSW and UFSW. These results show that the higher rotational speed of the tool and lower traveling speed of the tool help to achieve the best tensile properties of the welded joints made in both air and water within the experimented process parameters due to the generation of higher amount of heat and the proper stirring of the material by the rotating tool. The optimum result obtained at higher tool rotational speed and lower traveling speed for the different output responses by other researchers [5,6,23] using different optimization techniques supports the present result. The tensile properties of the base metal are as follows: Yield strength = 288 MPa; Tensile strength = 311 MPa, and %Elongation = 34.5. The observed % Elongation in both FSW in air and UFSW is very low when compared with the %Elongation of the base metal i.e., 1.5% and 3% of the base metal in air and UFSW respectively. From the experimental results, it is also noticed that the yield strength, ultimate tensile strength, and %Elongation of the joint made in water FSW using the optimal process parameters are 18.7%, 48.7%, and 100%, respectively, higher than the conventional FSW. The improvement in the strength of the welded joint underwater may be attributed to the hardening effect caused by the drastic cooling from the surrounding water. But, in the case of air FSW, the softening effect is caused by the slow cooling in the air. Further, an increase in the tool's traveling speed decreases the tensile properties drastically due to lower heat generation and improper stirring action by the tool.

The microstructure of the joints made using the above-mentioned optimum process parameters and also two more sample microstructures of the joints produced using the process parameters other than the optimum values are presented in Figure 6. Coarse-grained structures are observed (Figure 6(b) and (d)) in both FSW and UFSW in the process parameters other than the optimum values. Figure 6(a) and (c) reveals that the finer grain is formed due to stirring action by the higher rotational and lower traveling speed of the tool and are evenly distributed in both FSW and UFSW.

Thus, the hardness is higher in the stir zone than the parent metal, which increases the yield and ultimate tensile strength of the joint. More finer grains are formed in UFSW when compared to FSW due to the drastic cooling by the surrounding water, which results in higher tensile properties in UFSW than in FSW at optimum process parameters. Also, there is no evidence of defects, such as cracks, voids, etc, noticed in the observed microstructure of the joints formed in both air and water. The macrostructural view of a cross-section of the welded joint fabricated using the tool rotational speed of 500 rpm and tool traveling speed of 80 mm/min underwater is shown in Figure 7. Since the thickness of the sheet material is only 1 mm, the macrostructure does not clearly show the boundary layer between the different zones.

Figure 7. Macrostructure of the welded joints of UFSW 500 rpm 80 mm/min.

Overall, the strength of the welded joint depends on the following: (1) Sufficient generation of heat due to friction between the tool and the workpiece; (2) Proper mixing of plasticized material due to the stirring of the rotating tool; (3) The rate of cooling; and (4) Formation of the grains. The dominating combination of the above-said factors decides the strength of the welded joints in both air and underwater FSW.

4. Conclusion

The Friction Stir Welding (FSW) of titanium sheets was performed under an air and water environment and tested for the joint tensile properties. The Analytic Hierarchy Process (AHP) was used for calculating the weights of the relative importance of the factors, and the Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method of optimization was applied to obtain the optimum process parameters. From the obtained results, the following conclusions are derived:

- In AHP, the pairwise comparison of output responses for their quality of significance was made, and the weights of the relative importance were calculated and successfully checked for the acceptability and consistency of the assumed pairwise comparison of the responses;
- The VIKOR method, a multi-criterion and multi-response optimization technique, was implemented successfully in conventional and Underwater FSW (UFSW) to obtain the optimum process parameters;
- By the VIKOR optimization method, the optimal process parameters identified in air FSW are 500 rpm of tool rotation speed and 80 mm/min tool traversing speed;
- In the case of the Submerged FSW (SFSW) process, the optimal process parameters are 500 rpm and 80 mm/min from the VIKOR method;
- The results of the VIKOR method are supported by the results of the microstructural study.

Conflict of interest and funding

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Nomenclature

FSW	Friction Stir Welding
UFSW	Underwater Friction Stir Welding
SFSW	Submerged Friction Stir Welding
AHP	Analytic Hierarchy Process
VIKOR	Vlsekriterijumska Optimizacija I Kompromisno Resenje
LTW	Low-Temperature Water
RTW	Room-Temperature Water
HTW	High-Temperature Water
AISI	American Iron and Steel Institute
ANOVA	Analysis of Variance
RSM	Response Surface Methodology
CCD	Central Composite Design
SQP	Sequential Quadratic Programming gradient
CFD	Computational Fluid Dynamics
GRA	Grey Relational Analysis
ANN	Artificial Neural Network
ANFIS	Adaptive Neuro-Fuzzy Inference System
HHO	Harris Hawks Optimizer
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
PCA	Principal Component Analysis
DE	Differential Evolution
PSO	Particle Swarm Optimization
MCDM	Multi-Criteria Decision-Making
HCHCr	High Carbon High Chromium
YS	Yield Strength
TS	Tensile Strength
ASTM	American Society of Testing and Materials
GM_i	Geometric mean of ith row
W_j	Weightage of jth column
λ_i	Eigenvalue of ith row
CI	Consistency Index
RI	Random consistency Index
CR	Consistency Ratio
P	Normalized decision matrix
S_i	Utility factor of ith row
R_i	Regret factor of ith row
Q_i	VIKOR constant

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