Dry and underwater friction stir welding of aa6061 pipes - a comparative study

I. Sabry¹ and N. Zaafarani ²
¹Manufacturing Engineering Department, Modern Academy for Engineering and Technology, P.O. Box, Cairo 11571, Egypt
²Department of Production Engineering and Mechanical Design, Tanta University Tanta 31527, Egypt

Abstract. This work compared the parameters of friction stir welding (FSW) and underwater friction welding (UWFSW) on the weld joint, such as tool rotation speed, transverse speed, and wall thickness, and compare the ultimate tensile strength (UTS) weld joint using the experimental work for FSW and UWFSW was performed using a new modified fixture to eliminate the post-process problems. Experiments were performed at three levels of three parameters: Wall thickness, tool rotational speed and travel speed using milling machine center by UWFSW and traditional FSW. The full factorial approach was introduced for statistical research. UTS is measured as a reaction, meaning that the ultimate tensile strength achieved by welding the UWFS weld was greater than the conventional FSW weld. As a predictive research tool, regression analysis and variance analysis were used. From the study, it was observed that with minimal tool transverse speed, high tool rotation speed for UWFSW, maximum tensile strength is given, and that of traditional FSW.

1. Introduction
Four stages during friction stir welding (FSW) have been carried out: the plunging stage, the dwelling stage, the welding stage, and the escape or retracting stage of the tool [1]. The FSW procedure is essentially carried out by plunging a spinning FSW mechanism unit through the interface of two rigidly clamped sheets before the shoulder meets the surface of the material being welded [2] [3]. The travel of the unit progresses along the weld line allowing the material to displace from the advancing side to the retracting side. Meanwhile, the tool shoulder consolidates the material at the back of the pin, resulting in a stable state [4]. Compared to other conventional welding processes, FSW process uses a significant amount of energy. The absence of flux or cover gas makes the process environmentally safe [5].

The key parameters in the FSW process are welding speed, tool rotational speed, penetration depth, vertical and axial force, instrument tilt angle. They are critical in producing heat generation, forging strain, the flow of material, welding appearance, and performance. As an outcome of dislocation density increase, the nugget area has high stiffness at higher speeds [6]. Furthermore, the axial forces also shift at varying rotational speeds [7]. The softened area gets narrower as welding speed increases, and precipitate corrosion is weakened [8]. The ultimate tensile strength (UTS) of the welded joint is boosted by lower heat generation and high volume fraction of precipitate as a result of greater travel speeds, grain boundary reinforcement [9]. Maximum penetration demands maximum plunge depth,
otherwise it will lead to a decrease in loadbearing potential. The depth of penetration is seen to influence the consistency of the welds. There is a linear relationship between the shoulder force and torque and the penetration depth [10]. FSW is recommended for maximum depth [11]. The mechanical and metallurgical characteristics are depending on the environments, the base material and the consumables in general. The working environment to which the joint is exposed is often critical. There is a chance of crack expanding as the joint is exposed to high-pressure and high-temperature fluids, which stops the device itself from operating [12].

Khourshid et al [13] conducted FSW trials on AA6063 pipes using drilling machine. The purpose was to determine the feasibility of welding two pieces of aluminum pipes by the method of friction stir welding and to investigate the effect of the welding process on the mechanical properties of welding joints. The findings of using various mechanical tests on the welding joints reveal that aluminum pipes (AA6063) can be welded by the FSW process with ultimate tensile efficiency (78.7 %) based on the stir welding experiments carried out in this report, using a rotational speed of 1400 rpm, 4 mm/min travel speed. As a general result, the mechanical performance of FSW welds increases with increasing tool rotating speed and lowering the tool linear feed [13].

A major concern in the FSW is the significantly low weld strength. This happens as the continuous increase of the temperature causes the work material to soften and plasticized which indirectly leads to a decline in the mechanical properties of the welded joints. By increasing the cooling rate and lowering pick temperature this drawback effect can be minimized [14]. It was found that the frequency of further plasticized weld joint zone and poor mechanical characteristic arising from the breakdown of the reinforcing sediment in FSW is by contrast, less in the case of using the underwater friction stir welding (UWFSW) technique leading to less faulty welds compared to traditional FSW [15]. Another investigation [16] shows that using UWFSW method to join aluminum alloys and magnesium alloys significantly suppresses the formation of intermetallic compounds because of the lower peak temperature.

In order to refine the parameters involved in the UWFSW process, researchers have used computational methods and approaches such as GRA, Taguchi, ANN and RSM [17] [18]. The detection of defects is important for correlating experimental results with the model findings of the optimum weld quality parameters [19] [20]. Taguchi technique and ANOVA technique are considered to be a robust effective tool for carrying out experimental work and further processing the experimental data for optimization [2]. As outcome of abrupt cooling, the peak temperature produced is lower in UWFSW. However, the primary cause for the presence of lack of fill, tunnel defect and lack of penetration is the cooling of the weld area before filling the joint.

Although UWFSW is recognized recently as a hot research topic, few literatures are available on underwater welding of flat base metals. Literature on the method of UWFSW designed for soldering hollow cross-sectional tubing is very unusual. A research on the influence of parameters in the method of UWFSW is therefore important. In the past, experiments carried out on flat plates made of various aluminum alloys using UWFSW instead of FSW discussed an improvement in the ultimate tensile strength [23]. When the AA7075-T351 sample was welded using UWFSW, Zhao et al [22] found that the tensile strength of 75 % of the parent material was substantially higher in the weld region than in the FSW phase. A substantial reduction in both the diameter of the softened region and the softening ratio in the case of the AA6061 weld joint as a result of decreased peak temperatures with a joint performance of 86 % shows the importance of UWFSW in the joining industry [24]. The mechanical properties are closely related to metallurgical transformation [25]. Further grain refining is provided by liquid to sample contact in UWFSW, which creates a high cooling rate [26]. A UWFSW process will create the mechanical properties that are important for the homogeneity of welding joint [27].

In industrial practice welded AA6061 pipes is widely used, where different welding techniques, such as resistance welding, welding of inert metal steel, welding of inert tungsten gas, etc. are used. FSW and UWFSW can be a good alternative welding technique for this product. The current research considers the comparison of the UTSs of the weldments using both UWFSW and FSW for AA6061
pipes. In this context the ANOVA analysis is utilized as a modelling tool to identify the better method to be used from the UTS of the weldment point of view.

2. Experimental work

2.1 Material and Experimental Setup

The AA6061 pipes were chosen as work material to conduct the welding. The pipe has a diameter of 30 mm and a wall thickness of 2, 3 and 4 mm. Table 1 shows the chemical composition of the AA6061 material of the pipes and Table 2 shows the mechanical properties of AA6061.

| Element | wt.% |
|---------|------|
| Al      | Bal. |
| Si      | 0.61 |
| Fe      | 0.69 |
| Cu      | 0.26 |
| Mn      | 0.14 |
| Mg      | 0.19 |
| Ti      | 0.14 |
| Cr      | 0.19 |
| Zn      | 0.26 |

**Table 2 Mechanical Properties of AA6061**

| Description | AA6061 |
|-------------|--------|
| UTS         | 240 MPa|
| El %        | 15 %   |

2.2. Machine

A vertical milling machine (VMM) prepared and equipped for the FSW and UWFSW for pipe process was used as in [28]. The preparation of the machine usually involves a fixture design that can accommodate a rotating motion for the pipe. The rotating motion of the pipes here acts as the travel speed (F) to allow the advancing motion of the tool over the weld line figure 1.

**Figure 1** Experimental setup for (a) FSW (b) UWFSW
2.3 Fixture
The first fixture used in the FSW and UFSW for pipes process was composed of a solid rod back ended with a threaded part as shown in Figure 2(a) [29]. The two pipes are assembled on the rod and tightened with a washer and a nut. This fixture was efficient and provided several good quality samples. However, the issue was always to get off the pipes from this fixture after welding. Internal axial hammer support was used to perform this hard task. That stimulates to design a new fixture to eliminate this post welding hard task. In the new design, the solid rod is decomposed into two parts connected with alike gear teeth Figure 2 (a). After welding and loosing the nut, the rod two parts are disassembled, and every part is removed easily from inside the pipe welded.

2.4 Tool Design
Three special, non-consumable instruments constructed of 6 mm pin diameter Stainless steel 316 L [6] utilized to weld aluminium pipes. The pin profile was tapered with root diameter equal to 5 mm and the tip diameter was 1 mm and the pin length was 2, 3 and 4 mm. The pin was attached to the main tool body by a shoulder and a tip of conical shape with root diameter of 5 mm and head diameter of 1 mm. The tip height was 5 mm. The tool used is shown in Figure 3.

2.5 FSW and UWFSW process variables
The independent process parameters influencing the ultimate tensile strength (UTS) were defined as rotation speed (N) and travel speed (F), based on preliminary trials and previous studies. The friction-stir welding parameters are shown in Table 3.

| Parameter                  | Value                  |
|----------------------------|------------------------|
| Tool rotation [rpm]        | 485, 710, 910, 1120, 1400, 1800 |
| Wall thickness [mm]        | 2, 3, 4                |
| Transverse speed [mm/min]  | 4, 8, 10               |
Trial runs continued to evaluate the upper and lower limit of AA 6061 method parameters by modifying just one parameter at a time. A parameter set has been calibrated in such a way that no flaws were recognised by visual screening in the final welded joint. The upper limit was coded as 1 and the lower limit was coded as -1. The coded intermediate values were determined using equation (1).

\[ x_i = 2X - \frac{x_{max} - x_{min}}{x_{max} - x_{min}} \]  

(1)

where \( x_i \), \( x \), \( x_{max} \) and \( x_{min} \) are the coded value desired, the value of the variable, the lower limit of the variable, and the upper limit of the variable, respectively [20]. The process parameters considered, with their respectively boundaries, units and notations, are defined in Table 4.

| Process Parameters     | Unit   | Levels       |
|------------------------|--------|--------------|
| Tool rotation (N)      | [rpm]  | 485 1400 1800|
| Wall thickness (W)     | [mm]   | 2 3 4        |
| Tool feed rate (F)     | [mm/min]| 4 8 10      |

In order to carry out metallurgical experiments, specimens of the appropriate size were cut from the welded plate, as explained in figure 4(a). The FSW and UWFSW samples welded at 10 mm/min and 1800 rpm are illustrated in Figure 4(b) and Figure 4(c).

Figure 4 (a) Sample geometry of tensile test (b) A welded FSW sample (c) welded UWFSW sample welded

The experimental work was conducted on the milling machine. The welded sample's UTS were tested in compliance with ASTM D638-14[28]. In order to find relevant variables, ANOVA was used. Utilize a statistical analysis technique for and parameter at all stages, the main impact plots and their interaction plots were plotted to analyse the parametric effects on the features of the response. Utilize "Minitab 18" statistical program, all the findings were evaluated (Table 3).
3. Results and discussion

The goal of the analysis is to define the influence of FSW and UWFSW parameters using the full factorial system on the ultimate tensile strength. Primary impact plots and interaction plots were plotted utilizing ANOVA. The key impact plots have been used to analyse the parametric effects on the properties of the responses. All findings were analysed using statistical tools, "Minitab 18". The welded specimen UTSs were tested in accordance with ASTM D638-14. The outcome of the inspection welded component is as shown in Table 5.

Table 5 Experimental design matrix and results

| Run No. | N (rpm) | W (mm) | F (mm) | UTS (MPa) | FSW | UWFSW |
|---------|---------|--------|--------|-----------|-----|-------|
| 1       | 1800    | 2      | 4      | 205.0     | 218 |       |
| 2       | 1800    | 2      | 8      | 199.2     | 210 |       |
| 3       | 1800    | 2      | 10     | 195.0     | 202 |       |
| 4       | 1800    | 3      | 4      | 198.0     | 204 |       |
| 5       | 1800    | 3      | 8      | 193.8     | 200 |       |
| 6       | 1800    | 3      | 10     | 189.0     | 192 |       |
| 7       | 1800    | 4      | 4      | 190.9     | 196 |       |
| 8       | 1800    | 4      | 8      | 186.4     | 192 |       |
| 9       | 1800    | 4      | 10     | 183.0     | 186 |       |
| 10      | 1400    | 2      | 4      | 193.0     | 201 |       |
| 11      | 1400    | 2      | 8      | 187.2     | 194 |       |
| 12      | 1400    | 2      | 10     | 182.4     | 190 |       |
| 13      | 1400    | 3      | 4      | 186.6     | 189 |       |
| 14      | 1400    | 3      | 8      | 181.0     | 188 |       |
| 15      | 1400    | 3      | 10     | 176.0     | 184 |       |
| 16      | 1400    | 4      | 4      | 179.9     | 186 |       |
| 17      | 1400    | 4      | 8      | 174.1     | 182 |       |
| 18      | 1400    | 4      | 10     | 169.3     | 179 |       |
| 19      | 1120    | 2      | 4      | 184.0     | 190 |       |
| 20      | 1120    | 2      | 8      | 178.6     | 186 |       |
| 21      | 1120    | 2      | 10     | 173.0     | 181 |       |
| 22      | 1120    | 3      | 4      | 177.3     | 184 |       |
| 23      | 1120    | 3      | 8      | 171.0     | 180 |       |
| 24      | 1120    | 3      | 10     | 166.0     | 179 |       |
| 25      | 1120    | 4      | 4      | 169.8     | 181 |       |
| 26      | 1120    | 4      | 8      | 164.0     | 176 |       |
| 27      | 1120    | 4      | 10     | 159.0     | 168 |       |
| 28      | 1120    | 4      | 10     | 159.0     | 168 |       |
| 29      | 910     | 2      | 4      | 176.0     | 180 |       |
| 30      | 910     | 2      | 8      | 170.0     | 175 |       |
| 31      | 910     | 2      | 10     | 164.0     | 170 |       |
| 32      | 910     | 3      | 4      | 170.5     | 175 |       |
| 33      | 910     | 3      | 8      | 164.0     | 171 |       |
| 34      | 910     | 3      | 10     | 158.5     | 169 |       |
| 35      | 910     | 4      | 4      | 162.4     | 170 |       |
| 36      | 910     | 4      | 8      | 157.0     | 165 |       |
| 37      | 910     | 4      | 10     | 152.0     | 163 |       |
| 38      | 710     | 2      | 4      | 168.0     | 173 |       |
| 39      | 710     | 2      | 8      | 161.0     | 166 |       |
| 40      | 710     | 2      | 10     | 156.0     | 165 |       |
| 41      | 710     | 3      | 4      | 162.8     | 167 |       |
| 42      | 710     | 3      | 8      | 156.0     | 164 |       |
3.1 Mathematical Model

The ultimate tensile strengths of the FSW and UWFSW joints are functions of rotation speed, travel speed and wall thicknesses and can be expressed as in equation (2).

\[ Y = f(N, F, W) \] (2)

The UTS value may be considered as a response Y in equation 2. The selected polynomial equation could be expressed as an equation for the three variables as follows:

\[ Y = \beta_0 + \beta_1 N + \beta_2 F + \beta_3 W + \beta_{11} N^2 + \beta_{22} F^2 + \beta_{33} W^2 + \beta_{12} NF + \beta_{13} NW + \beta_{32} WF \] (3)

where \( \beta_0 \) is the free term of the regression equation; \( \beta_1, \beta_2 \) and \( \beta_3 \) are the linear terms; the coefficients \( \beta_{11}, \beta_{22} \) and \( \beta_{33} \) are quadratic terms; the coefficients \( \beta_{12}, \beta_{13} \) and \( \beta_{32} \) are the interaction terms. The values of the coefficients of the polynomial were calculated by regression analysis with the help of the following four equations [30]:

\[ \beta_0 = 0.1663 \sum(Y) - 0.0568 \sum(X_{ij}Y) \] (4)
\[ \beta_1 = 0.0732 \left( \sum(X_j)Y \right) \] (5)
\[ \beta_i = 0.0625 \sum(X_{ij}Y) + 0.00689 \sum(X_{ij}Y) - 0.0568 \sum(Y) \] (6)
\[ \beta_{ij} = 0.1250 \sum(X_{ij}Y) \] (7)

where \( i \) and \( j = 1, 2, 3 \) and \( i < j \)

The software package DESIGN Specialist 8.0.4 was used to approximate the values of these coefficients for various answers, and the results are shown in Table 6.

**Table 6** Calculated statistical model regression coefficients for FSW and UWFSW

| Regression factor | Tensile strength (MPa) |
|------------------|------------------------|
|                  | (FSW)                  |
| \( \beta_0 \)    | 174.3                  |
| \( \beta_1 \)    | 23.81                  |
| \( \beta_2 \)    | -6.576                 |
| \( \beta_3 \)    | -5.405                 |
| \( \beta_{11} \) | -2.989                 |
| \( \beta_{22} \) | -0.7667                |
| \( \beta_{33} \) | -1.215                 |
|                  | (UWFSW)                |
| \( \beta_0 \)    | 148.0                  |
| \( \beta_1 \)    | 0.06387                |
| \( \beta_2 \)    | -6.341                 |
| \( \beta_3 \)    | -0.02761               |
| \( \beta_{11} \) | -0.0000051             |
| \( \beta_{22} \) | 0.8056                 |
| \( \beta_{33} \) | -0.09722               |
Minitab software was used to formulate the regression equations (8 and 9) that predict the average response of UTS of the UWFSW joints as a function of UWFSW processing parameters (wall thickness, rotational speed, and transverse speed). The levels of the UWFSW process parameters used in the regression model and their corresponding codes are shown in Table 6. By residual analysis, the adequacy of the suggested regression models is tested. The residual maps, histogram and standard probability for the UTS are seen in Figure 5. For both weld methods the standard probability map and the frequency histogram of the residuals show that errors are typically distributed. Moreover, residual versus fitted value or observation order plots do not suggest any significant inadequacies in the model.

\[
\begin{align*}
\beta_{12} & = -0.1676 - 0.00479 \\
\beta_{13} & = 0.7726 - 0.0005347 \\
\beta_{32} & = 0.1723 + 0.1815
\end{align*}
\]

By residual analysis, the adequacy of the suggested regression models is tested. The residual maps, histogram and standard probability for the UTS are seen in Figure 5. For both weld methods the standard probability map and the frequency histogram of the residuals show that errors are typically distributed. Moreover, residual versus fitted value or observation order plots do not suggest any significant inadequacies in the model.

\[
\begin{align*}
UTS\,(FSW) & = 146.2 + 0.05003N - 2.081W - 0.5320 F - 6.914E006N^2 - 0.7667W^2 - 0.1350F^2 - 0.000254 NW + 0.00039NF + 0.05744WF \\
UTS\,(UWFSW) & = 148 + 0.06387N - 6.341W - 0.0276 F - 5.181E006N^2 + 0.8058 W^2 - 0.097F^2 - 0.000479 NW - 0.000534NF + 0.1815WF
\end{align*}
\] (8) (9)

Figure 5. Residuals plot for UTS (a) UWFSW (b) FSW

UTS was maximum at higher tool rotation speed, and UTS was minimal at lower tool rotation speed. At lower tool transverse speed, the full UTS value was reached. For wall thickness, at higher wall thickness, the UTS was maximally reached Figure 6 (a). Tool rotation speed of 1800 rpm, tool transverse speed of 4 mm/min, and wall thickness of 2 mm were the optimal process parameters for the FSW without using water to gain the highest weld strength. It is seen in Table 7 that the parameters influencing UTS were investigated using ANOVA.

Figure 6(b) depicts the plots of the main effects of UTS. It shows that travel speed has a higher significant effect on UTS than the other parameters and the effect of this factor is directly proportional to UTS responses. It can be stated that the increasing of travel speed causes the UTS to increase significantly. The travel speed of 10 mm/min shows lower UTS values. The rotational speed of 1800 rpm shows higher UTS, wall thickness also shows an effect on UTS.
3.2 Checking the adequacy of the built models for FSW using ANOVA
The adequacy of the specialised models hires the variance methodology analysis (ANOVA). The percentage of contribution (p) signals the parameters for the linear square and interaction phase with the response functions. These (p) values are used to classify the significant response function parameters [31]. Table 7 displays the effects of ANOVA’s tensile strength model. The 1929 F-value (FSW) model and the 312 F-value (UWFSW) for tensile strength indicate that the model is significant. Due to noise, there is only a 0.01 percent probability that a model F-value will occur. Values outside the interval [0 1] imply that the terms of the model are not important. The coefficient of determination $R^2$ values gives the adequacy of fitness of the model. Table 7 describes the determined values of the established model.

|                        | F-value | $R^2$  | Adjusted $R^2$ | Predicted $R^2$ |
|------------------------|---------|--------|----------------|-----------------|
| Tensile strength (UWFSW) | 312     | 0.9494 | 0.9463         | 0.9391          |
| Tensile strength (FSW)  | 1929    | 0.9914 | 0.9905         | 0.9898          |

3.3 Comparison of all Parameters with Respect to UTS
Comparison of all processes is recommended in order to determine the best properties obtained by the process with or without the use of water. A graphical approach was used for greater interpretation or better analysis of both methods. For both processes, the bar chart was created. The graph is as shown in Figure 7. It is evident from the graph that the UTS attained by the UWFSW is greater than the UTS attained by the FSW [6]. The overall UTS obtained using UWFSW and FSW were 225 MPa and 205.4 MPa, respectively.

![Figure 6. Main effect plot for (a) FSW (b) UWFSW](image)
3.4 Influences of process parameters from FSW and UWFSW
Using the experimental findings presented in figure 8, the tensile strength of FSW and UWFSW welded aluminium alloy 6061 was predicted by mathematical simulations, demonstrating the general patterns between the predicted and experimental performance. The ANOVA results are given in Table 7. By drawing scatter diagrams presented in Figure 8, the validity of regression models established is further checked (a-b). The observed values and the expected response values are scattered close to the 45° axis, suggesting that the established empirical models match almost perfectly [19]. At a greater rotation speed of 1800 rpm, the rise in UTS for UWFSW is important, although a slight decrease in UTS for FSW at a rotation speed of 1800 rpm is observed.

3.5 Analysis of results
In Figure 9 (a and b), showing the general patterns between cause and effect, the effects of the various process parameters on the mechanical properties of FSW and UWFSW welded aluminum alloy AA6061 are estimated from the mathematical models using experimental observations. The contour graph of tensile strength, for FSW and UWFSW, is shown in Figure 9.

3.6 Microstructure Study
Because of the thermomechanical mechanism of FSW, and UWFSW, both the material flow and the heat dissipation rate will induce metallurgical transformations, altering the mechanical properties. Figure 10 (a) demonstrates the microstructure of welded zone under various welding stipulation. It is

![Figure 8 Scatter diagram of predicted and experimental UTS (a) FSW (b) UWFSW](image)

![Figure 9 Bar chart displaying the overall desirability value of 0.915 for the combined desirability value](image)

![Figure 10 Microstructure study](image)
shown that from FSW to UWFSW, grain size is decreased. Thus, at the same time, the application of cooling results in high angle grain boundaries because higher dislocation density and dynamic recovery and finally fine grain size. Figure 10 (b) shows the optical microscopic image of the heat affected zone (HAZ) and nugget zone (NZ). Two zones - the nugget zone and heat affected zone by heat were clearly distinguishable from the joint weld 's optical microscopic image. This implied the need to examine the mechanical properties of the joint because of the unusual distribution of the material in the weld zone.

Figure 10 The microstructure of weld cross-section of AA6061 using (a) FSW (b) UWFSW UTS

4. Conclusions

An experimental distinction between FSW and UWFSW on Al6061 alloys is provided in this research paper. For the analysis of the work, ANOVA was carried out and regression was also performed; the following conclusions were reached:

1. UTS decreases as the speed of travel increases and UTS increases as the speed of travel decreases in UWFSW and FSW.
2. UTS has attained speed at a lower tool transverse speed of 4 mm/min, and tool transverse speed increases by 10 mm/min and UWFSW UTS decreases.
3. Wall thickness at 4 mm in UWFSW, UTS increases up to a certain level after that level and then decreases at wall thickness 2 mm and on the other hand in FSW at wall thickness 2mm leads to UTS increases up to a certain level after that level and then decreases at wall thickness 4 mm
4. In FSW and UWFSW, at higher tool rotation speed, UTS increases, and as tool rotation speed decreases, UTS decreases.
5. UWFSW add additional hardness in the sample in two areas-nugget zones and heat-affected zone. Because of the existence of small grains this is believed as in specimens welded utilizing standard FSW.
6. Water decreases the distribution of temperature in together UWFSW conditions but during the FSW phase, the effect of in-temperature is evident.

References

[1] I. S. A.M.El-Kassas 2019 A New Quality Monitoring System for Friction Stir Welded Joints of Aluminum Pipes Int. J. of Eng. and Tech. 11 78–87.
[2] I. S. A.M.El-Kassas 2018 Comparative Study on Different Tool Geometrics in Friction Stirred Aluminum Welds Using Response Surface Methodology 4th Int. Conf. on Weld. and Fail. A. of Eng. Mat., Aswan, Egypt.
[3] E. H. a. R. I. A. Ibrahim Sabry 2019 Improvement of Mathematical Model to Predict the Mechanical Properties and Corrosion rate of Friction Stir Welded 2024 Aluminum Alloy in 2nd Int. Conf. on Mater. Sci. and Eng. Egypt.

[4] Z. A. a. N. Mohd. Atif Wahid 2018 Review on underwater friction stir welding: A variant of friction stir welding with great potential of improving joint properties Trans. of Nonferr. Meta. Soc. of China 28 193-219.

[5] I. S. A.M. El-Kassas 2017 A Comparison between FSW, MIG and TIG Based on Total Cost Estimation for Aluminum Pipes Europ. J. of Adv. in Eng. and Tech. 4 158–163.

[6] A.-H. I. M. D. T. Ibrahim Sabry 2020 Comparison of Mechanical Characteristics of Conventional and Underwater Friction Stir Welding of AA 6063 Pipe Joints Inter. Rev. of Aerosp. Eng. 14 64-70.

[7] P. B. M. H. a. C. . H. Papahn 2015 Study on governing parameters of thermal history during underwater friction stir welding Inte. J. of Adva. Manuf. Techn. 78 1101–1111, 2015.

[8] H. J. Z. a. L. Y. H. J. Liu 2011 Effect of welding speed on microstructures and mechanical properties of underwater friction stir welded 2219 aluminum alloy Mat. and desig. 32 1548–1553.

[9] S. M. a. V. B. S. Sabari 2016 Influences of tool traverse speed on tensile properties of air cooled and water cooled friction stir welded AA2519-T87 aluminium alloy joints J. of Mat. Proce. Techn.237 286–300.

[10] A. S. I. M. A. T. D. El-Kassas 2019 Characteristics of Potential Sources - Vertical Force, Torque and Current on Penetration Depth for Quality Assessment in Friction Stir Welding of AA6061 Pipes Inter. Review of Aerosp. Eng. 4 195-204.

[11] M. E.-S. M. K. A. Youssif 2016 Influence of Critical Process Parameters on the Quality of Friction Stir Welded Nylon 6 Inter Review of Mech. Eng. 7 501-507.

[12] S. N. a. A.-H. I. M. S. K. Maiti 2008 A scheme for finite element analysis of mode I and mixed mode stable crack growth and a case study with AISI 4340 steel Nucl. Eng. and Desig 238 787–800.

[13] L. S. F. S. w. S. o. A. P. A. M. Kourshid 2013 friction stir welding study on aluminum pipe Int. J. of Mech. Eng. and Robot. Resea. 2 331-339.

[14] N. G. M. A. G. a. M. A.-M. Ibrahim Sabry 2020 Optimization of Process Parameters to Maximize Ultimate Tensile Strength and Hardness of Underwater Friction Stir Welded Aluminium Alloys using Fuzzy Logic Mod. Concep. in Mater. Sci 3 73–78.

[15] I. S. A.M. Kourshid 2013 Analysis and Design of Friction Stir Int. J. of Mech. Eng. and Robot. Resea. 2 333-341.

[16] A.-Z. A. G. F. G. C. Mofid MA 2012 Submerged friction-stir welding (SFSW) underwater and under liquid nitrogen: an improved method to join Al alloys to Mg alloys Miner. Met. Mater. Soc. 43 5106–5114.

[17] A. M. E.-K. a. A. K. Ibrahim Sabry 2015 Integration between Artificial Neural Network and Responses Surface Methodology for Modeling of Friction Stir Welding Int. J. of Adv. Eng. Rese. and Sci. 1 67-73.

[18] I. S. Ahmed M. El-Kassas 2019 Optimization of the Underwater Friction Stir Welding of Pipes Using Hybrid RSM-Fuzzy Approach Int. J. of App. Eng. Rese. 14 4562-4572.

[19] Ibrahim Sabry and M. Abdel Ghaafar Nabil Gadallah 2019 A Summarized Review on Friction Stir Welding for Aluminum Alloys in 3rd Int. Conf. Arch., Eng. and tech. (AET). Cairo, Egypt.

[20] H. Z. Y. a. Y. U. L. . H.-J. Liu 2010 Mechanical properties of underwater friction stir welded 2219 aluminum alloy Trans. Nonferrous Met. Soc. China 20 1387–1391.

[21] Q. W. H. a. K. Y. Y. Zhao 2014 Microstructure and mechanical properties of spray formed 7055 aluminum alloy by underwater friction stir welding,” Mat. and desig., 56 725–730.

[22] M. E.-S. M. K. A. Youssif 2016 Influence of Critical Process Parameters on the Quality of Friction Stir Welded Nylon 6 Inter Review of Mech. Eng. 7 501-507.

[23] K. K. a. H. T. D. Sakurada 2002 Underwater friction welding of 6061 aluminum alloy,” J. Japa. Inst. of Light Meta. 52 2-6.
[25] M. A. a. A. E. D. A-H. I. Mourad 2014 Study on the mechanical behavior of aluminum alloy 5083 friction stir welded joint ASME Pressure Vessels and Piping Conf., PVP2014-28556, V06AT06A014.

[26] D. C. H. a. K. S. Vecchio 2007 Thermal history analysis of friction stir processed and submerged friction stir processed aluminum Mate. Sci. and Eng. A 465 165–175.

[27] H. J. Z. a. L. Y. H. J. Liu, 2011 Homogeneity of mechanical properties of underwater friction stir welded 2219-T6 aluminum alloy J. of Mater. Eng. and Perf. 20 1419–1422.

[28] E.-K. A. Ibrahim Sabry 2019 An appraisal of characteristic mechanical properties and microstructure of friction stir welding for Aluminium 6061 alloy – Silicon Carbide (SiCp) metal matrix composite.,” J. of Mech. Eng. and Sci. 13 5804–5817.

[29] A. M. E.-K. A.-H. I. M. D. T. T. . J. A. Q. Ibrahim Sabry 2019 Friction Stir Welding of T-Joints: Experimental and Statistical Analysis J. of Manuf. and Mater. Proce. 3 2-23.

[30] W. G. Cochran and G. M. Cox 1957 Experimental Designs”, 2nd edition, New York, John Wiley & Sons Inc., 350.

[31] I. S. Ahmed M. El-Kassas 2019 Using Multi Criteria Decision Making in Optimizing the Friction Stir Welding Process of Pipes: A Tool Pin Diameter Int. J. of App. Eng. Rese. 14 3668-3677.