Influence of Temperature on Fatigue Life for Friction Stir Welding of Aluminum Alloy Materials

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Abstract—The industrial applications of aluminum alloys have a wide range in mechanical engineering, therefore, the welding of aluminum alloy is very important in production of a structure combined from aluminum alloy materials. Thus, the friction stir welding technique is used to welding the aluminum alloy materials, thus, the investigation for effect of temperature and other parameters on the friction stir welding will be carried out. Also, since the aluminum alloys used in most engineering applications is subjected to fatigue load, therefore, fatigue life in friction stir welding including the effects of temperature should be studied. The investigation included the evaluation the fatigue life of welding by using experimental techniques. The experimental technique covered manufacturing fatigue device for friction stir welding with effect of different temperature (75, 100, 125, and 150 °C), and then, measurement the fatigue behavior for welding was achieved. The experimental work included the evaluation of the tensile properties and the microstructure for friction stir welding. Where, the aluminum alloy studied in this work is aluminum alloy 2024. The results showed that the fatigue life for welding of aluminum alloy decreases with increasing the temperature applied on the alloy materials. Also, the results showed that the tensile properties for friction stir welding are the best at rotation speed (1800 RPM). Finally, the experimental fatigue results with and without temperature effect are compared with numerical fatigue results calculated by using finite element methods by adopting Ansys program Ver. 16.1. The comparison of fatigue results for friction stir welding gave a good agreement between experimental and numerical techniques used with maximum discrepancy about (9.7%).

Index Term—Friction Stir Welding, Fatigue Limit, Temperature, Aluminum Alloy.

I. INTRODUCTION

One of new thermo-mechanical processing used in welding the aluminum alloy is the friction stir welding technique which depends on the welding two parts of materials samples by melting of metal by a friction processing technique. Therefore, the friction stir welding gives a maximum performance for microstructure and mechanical properties with low cost and time. Also, the friction stir welding are applicable for various alloys welding which gives fine grained, equiaxed, and homogeneous microstructure. \cite{1}.

The friction stir welding characterizations, as tensile strength and fatigue behavior, and used for different alloys with various friction stir processing parameters are studied by many researchers. Therefore, the following papers followed the same investigation for friction stir welding characterizations, At, (2003), Y. J. Chao et al. \cite{2}, investigated the heat transfer between the tool and the well through friction stir welding. The investigation included the experimental and numerical techniques, by using finite element method, the heat generation due to friction stir welding are evaluated. The results showed that the heat flow with 5% through the tool and 95% flow through the work-piece. Also, H. J. Liu et Al, \cite{3}, presented evaluating of mechanical tensile properties for fracture location of friction stir welding of aluminum alloy types (2017-T351). The mechanical tensile properties for fracture joint are evaluated by using experimental techniques, where, the tensile properties are calculated with various parameters to investigate the effect of friction stir processing. In addition, the results showed that the maximum properties for friction stir welding joint obtained at friction stir processing with parameters as, 0.07 mm/rev pitch, 100 mm/min welding speed, and 1500 rpm rotation speed.

At, (2009), N. Sun et al. \cite{4}, studied the modified of microstructure for friction stir welding with different parameters effect. In addition, the investigation included measurement of thermal conditions of friction stir processing, in addition to, investigation the effect of temperature on the microstructure resultant. Where, the investigation studied for aluminum alloy types (A206) with 25.4 mm thickness. After this, in (2012), E. T. Akinlabi et al. \cite{5}, presented a non-destructive test for aluminum alloy type (5754) and copper type (C11000) welding by friction stir welding. The testing for friction stir welding joint investigation with various friction stir processing parameters effects as, rotation aped of tool and feed rate. The results showed that the rotation speed of tool 950 rpm with various rates feed gave the best welding joints between two materials welded.

Then, in (2013), J. De Backer e. al. \cite{6}, investigated the measurement of temperature between tool and work-piece for friction stir processing by using thermoelectric method. Where, the thermolectric method can be used to measure the variation of temperature quickly with different friction stir processing parameters effects.

Also, in (2013), P. J. Ramulu et al. \cite{7}, investigated the load extension of friction stir welding for aluminum alloy (Al 6061) with different parameters effects. The investigated parameters are, depth of plunge, diameter for shoulder tool,
rotation speed of tool, and speed welding. The results showed that the decreasing of diameters for shoulder, increasing the rotation speed welding, and increasing the speed welding lead to increasing the maximum load.

In (2016), G. Bihlaw et al. [8], investigated different thermal models for friction stir welding using numerical technique by adopting Ansys program. The investigated models are, the nonlinear and the transient thermal for friction stir welding for copper plate, with transverse and rotation speed effects. Also, V. C. Sinha et al. [9], presented the effects of rotation speed and travel speed effects on mechanical properties and microstructure for friction stir welding of Aluminum alloy and copper materials. In addition, the rotation speed effect on the different forces (axial and traverse force) and torque values were also carried out.

At. (2017), A. C. F. Siva et al. [10], measured the temperature during friction stir welding with various methods. The three techniques are used or measurement the temperatures in tools and workpiece by using thermocouples, and method for tool-work-piece. The results showed that the tool-work-piece method is the best method.

Finally, M. J. Jweeg, K. K. Resan, A. M. Takhakh and other researchers in (2011 to 2017), [11-23], presented various investigations for friction stir welding and friction stir processing, in addition to the investigation different rotation speed and other parameters effects on the friction stir welding strength, fatigue, residual stresses, optimization conditions of friction stir welding, and other characteristics. The investigation included the evaluation the mechanical tensile strength, fatigue characterizations, temperature effect on microstructure, and other characterizations for friction stir welding with different effect of rotation speed of tool and feed speed influence, in addition to the other parameters effects.

Different techniques were used to analyze the friction stir welding for various alloy materials using experimental and numerical techniques. Also, the studied cases showed that the best rotation speed and other parameters effects gave the best values of properties and behavior for friction stir welding.

In the field of the presented work showed that the researchers investigated the effect of different friction stir processing parameters on the mechanical properties, fatigue behavior, residual stress, and other characterizations of friction stir welding. The researchers works did not cover the investigation of the temperature effects on the fatigue characterizations of friction stir welding with various rotation speeds. In this work, the effect of different temperatures on the fatigue strength and life for friction stir welding with various rotation speeds are achieved through experimental and numerical techniques by using finite element technique with Ansys program, and then, a comparison study of the fatigue results is carried out.

II. EXPERIMENTAL WORK

The experimental work of friction stir welding included three parts, first, measuring the tensile test for friction stir welding to evaluate the mechanical properties for welding, and second, evaluating the microstructure for friction stir welding by using optical microscope, and finally, measurement the fatigue characterizations of friction stir welding with and without temperature effects. The friction stir welding is applicable for aluminum alloy types (2024). The yield strength about (345 MPa) and ultimate strength about (483 MPa), [24]. In addition, the aluminum alloy (2024) used have the following chemical composition, as, Mg, about 1.25 WT%, Si, about 0.87 WT%, Cu, about 5.75 WT%, Mn, about 0.535 WT%, Ti, about 0.014 WT%, and Cr, about 0.008 WT%, where, the characteristics for aluminum alloy (2024) cab be summarized as follows,

i. Acceptance for coating.
ii. High workability.
iii. High strength.
iv. Good resistance of corrosion.

Therefore, due to its high mechanical properties, the 2024 aluminum alloy and the friction stir welding have various engineering applications, such as fittings of aircraft, lens mounts, camera, fittings of hardware, fittings of marines, couplings, fittings of electrical, and decorative or misc.

The experimental work used two aluminum alloy plates with dimensions, as, length of plates 200 mm, width of plates 75 mm, and thickness of plates 3 mm.

Where, the plates are welded by using friction stir welding tool. Thus, the friction stir welding combined from two parts with various diameters, the first part is the shoulder part with 18 mm diameter, and, the second part is the taper pin with $D = 4 \times 3.5$ mm, as shown in Fig. 1.

In addition, the fixed for plates samples can be manufactured by using CNC M70V milling machine, as shown in Fig. 2. Where, the CNC M70V milling machine composed from various parts, as,

i. Friction stir welding tool, shown in Fig. 2.
ii. Standing plate.
iii. Claps and fixtures.
iv. Digital and manual control.

The fixed the aluminum sheet plates sample with machine, can be welded the plates sheet by friction stir welding techniques, and then test the friction stir welding section with various mechanical tests.

![Fig. 1. Friction Stir Welding Tool.](image-url)
The characterization for friction stir welding can be evaluated from the tensile test for friction stir welding and the fatigue test with and without effect of temperature variations. In addition, to evaluate the fatigue behavior of friction stir welding, manufacturing fatigue device to test the fatigue behavior with and without temperature effects of friction stir welding, and gives the stress-number of fatigue cycle for materials. The fatigue device manufactured was used as fatigue-creep interaction device which is used for the application of the temperature on fatigue sample. The manufacturing of the container part surrounding with fatigue sample is achieved to raise the temperature by using air heater. Finally, examination the friction stir welding section to give the microstructure for its section with various zones for optical microscope device.

II.1. Tensile Test Welded Sample
The tensile test used to evaluate the mechanical properties of welding section for plates sample welded. The tensile sample made corresponded to the ASTM standard (ASTM E8M), [25]. Where, tensile sample made with dimension and shape by using C-TEK machine, dependent on ASTM E8M standard, as shown in Fig. 3. Then, by polishing the sample surface to remove the flash for materials production due to tool shoulder rotating. Therefore, the tensile test for sample application by using tensile test machine with using (1 mm/ min) for testing welding samples.

In addition, the welding of plates are made with different rotation speeds, as, 1600 RPM; 1800 RPM; 2000 RPM; and; 2200 RPM, then, the tensile test for friction stir welding sample testing for various rotation speeds. Then, for each tensile sample with rotation speed testing five samples, and then, using the average value of tensile strength, [26,27], of friction stir welding with rotation speed.

II.2. Microstructure of Welding Sample
The microstructure test included examinations the microstructure for friction stir welding with various zones on the friction stir welding, as, i. NZ section, nugget zone. ii. TMAZ, thermo-mechanically affected zone. iii. HAZ, heat affected zone. Where, the microstructure for friction stir welding testing is achieved by using optical microscope, where, the testing included devaluing the grain structure and the morphologies for welding section. Thus, to prepare the welding sample, first, grinding the welding sample by using various emery papers, [28], and then, second, solution for etching involved by depending on the ASTM standard E407-76, where, its standard included using a killer’s etchant with the characterizations, as, 2 ml HF; 3 ml HCL; 5 ml HNO3; and; 190 ml H2O, [29].

II.3. Friction Stir Welding Fatigue Test
The fatigue test for friction stir welding included the constructing the stress-number of fatigue cycle for welding with various rotation speeds and with and without effect of temperature. The fatigue characterizations are evaluated by testing twelfth samples for each welding test conditions. Thus, the fatigue sample is made with shape and dimension, as shown in Fig. 4., are as follows,

i. Length of fatigue sample is 100 mm.
ii. Width of fatigue sample is 10 mm.
iii. Thickness of fatigue sample is 3 mm.
The fatigue shape and dimensions design depends on the fatigue device. Therefore, manufacturing and design fatigue device to evaluate the fatigue characterizations for friction stir welding, as shown in Fig. 5. Where, the fatigue device design and working are as follows,

i. Electric motor, at heavy base from one end.
ii. Motor shaft, to drive a counter shaft by V-belt drive, where, using substantial bearing cylinder to running the counter shaft.
iii. Shaft carries, used to carry the aluminum pulley, which is driven from motor, from one end. Also, the shaft carries used to carry the link between the reciprocating mechanism and the shaft, which is aluminum bush, form other end.
iv. Inductive proximity sensor, used beside the bush, this sensor gives at each turn signal to the counter.
v. Aluminum container, for covering reciprocating mechanism and the machine part included the fatigue sample.
vi. Container, to keep a temperature on the fatigue sample with constant temperature. The air heater is used to apply the temperature by container.

Therefore, the motor is rotating with different speeds and controller on the motor by control part amount on the device. Where, the reciprocating mechanism mount is used to apply the fatigue load on the fatigue sample, [30,31].

![Fig. 5. Fatigue-Creep Interaction Device](image)

Then, after manufacturing the fatigue samples, as shown in Fig. 4, using the rotation speeds, 1600 RPM to 2200 RPM, testing the samples with and without effects of temperature to evaluate the fatigue characterizations of friction stir welding with various parameters effects, by using fatigue device shown in Fig. 5. Thus, the temperatures investigations are, 75 °C, 100 °C, 125 °C, and 150 °C.

Therefore, to verify the validity of the fatigue results obtained through the manufacturer device, comparison the results by numerical fatigue results evaluating by using finite element techniques with using Ansys program Ver. 16.1, [32-58].

### III. NUMERICAL INVESTIGATION

The fatigue characterizations for friction stir welding are evaluated also by using numerical technique with finite element method technique, by using Ansys program Ver. 16.1. Where, the numerical results for fatigue behavior are compared with experimental results for fatigue to show the agreement of results. Therefore, for the analysis of the sample to fatigue characterizations with Ansys, firstly, the finite element must be selected for discretization purposes. Thus, the element type selected in Ansys program is Solid 187-3D-10-node with three degree of freedom at each node, as shown in Fig. 6, [59-65].

![Fig. 6. Geometry and Nodes for Solid 187 Element](image)

Then, after manufacturing the fatigue samples, as shown in Fig. 4, using the rotation speeds, 1600 RPM to 2200 RPM, testing the samples with and without effects of temperature to evaluate the fatigue characterizations of friction stir welding with various parameters effects, by using fatigue device shown in Fig. 5. Thus, the temperatures investigations are, 75 °C, 100 °C, 125 °C, and 150 °C.

Therefore, the solid 187 element have ability to model the multi mechanical engineering problem and materials as, application for early in-compressible elasto-plastic, fully incompressible hyper-elastic, orthotropic materials properties and direction, anisotropic materials properties and direction..and fatigue and creep application.

Therefore, the element required many input data to have the output characterizations for application. There, the input required data for element are the materials properties, materials types, application geometry, application problem, the boundary condition, applied load types and direction, and the behavior types for problem. Then, the output for element can be evaluated as nodal solution or as element results.

For fatigue application, by Ansys program, required input data are, the strength properties for friction stir welding calculated from experimental part, and, the fatigue stress-number of cycle behavior of friction stir welding measurement from experimental work. Then, the output of Ansys program are obtained as the fatigue characterizations with various rotation speed effects. In addition, the numerical results included the evaluation the fatigue characterizations for friction stir welding with and without effect of temperature. Finally, the numerical results calculated of fatigue characterizations, with and without temperature effects with various rotation speed, are compared with experimental results.
IV. RESULTS AND DISCUSSION
The results for fatigue characterization for friction stir welding with temperature effect were presented with three parts. First results part included the yield strength for friction stir welding, second, microstructure for friction stir welding with different zone, and the third part, included the evaluation of the fatigue characterizations for friction stir welding.

IV.1. Tensile Test Results
The tensile results include the evaluating the yield strength for friction stir welding with various rotation speeds. Where, the results are measured by experimental technique by testing five tensile samples for each rotation speed, and then, evaluating the average value for its samples, as shown in Fig. 7. Thus, the tensile yield strength for friction stir welding with various rotation speed effects are shown in Table I and Fig. 8. Therefore, from the table and the figure, it can be seen that the minimum strength of friction stir welding occur with rotation speed at 1600 RPM, and then increases to the maximum value at rotation speed 1800 RPM. The tensile yield strength of friction stir welding samples decreases with increasing the rotation speed, as for samples C and D.

![Fig. 7. Experimental Tensile Test Results of Samples for Friction Stir Welding with Different Rotation Speed.](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rotation Speed (RPM)</th>
<th>Yield Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1600</td>
<td>186</td>
</tr>
<tr>
<td>B</td>
<td>1800</td>
<td>309</td>
</tr>
<tr>
<td>C</td>
<td>2000</td>
<td>275</td>
</tr>
<tr>
<td>D</td>
<td>2200</td>
<td>237</td>
</tr>
</tbody>
</table>

IV.2. Microstructure Results
The second part of experimental work included evaluating the microstructure for friction stir welding with different welding zone. Figs. 9 to 11. show the microstructure for three zone of welding, as, the nuggets zone (NZ), thermo-mechanical affect zone (TMAZ), and the heat affect zone (HAZ), respectively. Where, the microstructure test for sample (B), with maximum tensile strength with rotation speed effect. From Fig. 9, it can be seen that, due to generation of high temperature and other friction stir processing parameters effect, the microstructure for nugget zone is fine recrystallized and refined. Also, due to same reason it can be seen that, as in Fig. 10, the microstructure for thermo-mechanical zone is observed elongated. Finally, the microstructure for heat zone, due to same reason, is semi recrystallization, as in Fig. 11.

![Fig. 9. Microstructure for Nugget Zone of Friction Stir Welding.](image)

![Fig. 10. Microstructure for Thermo-Mechanically Affected Zone of FSW.](image)
IV.3. Fatigue Results

The fatigue investigation included evaluating the fatigue strength and fatigue life for friction stir welding with various temperature effects and different rotation speed effects. Therefore, the investigation of fatigue characterizations included, first, evaluating the fatigue strength-number of cycle for sample B, at 1800 RPM with maximum tensile strength, by using experimental technique with different effects of temperature, and then, a comparison of the results with numerical results evaluated by finite element method, using Ansys program. A comparison between experimental and numerical fatigue results are presented in Fig. 12, and its results showed that the maximum discrepancy between results is about (9.7%). This percentage gives an indication for a good agreement for results evaluated by two techniques used.

The comparison of the fatigue results, showed the acceptable agreement of experimental and numerical technique, then, evaluating the fatigue characterizations for friction stir welding with different rotation speeds and temperature effects, as shown in Fig. 13. The rotation speed used are 1600 RPM, 1800, RPM, 2000 RPM and 2200 RPM, and the temperatures are, 25 °C (Room temperature-without temperature), 75 °C, 100 °C, 125 °C, and 150 °C. The fatigue characterizations, with various parameters effects are evaluated by using experimental techniques. The acceptable fatigue strength and life are for sample B (at 1800 RPM).

In addition, from Fig. 14, it can be seen that the fatigue strength for friction stir welding decreases with increasing the temperature. Fig. 14, shows that the fatigue strength for friction stir welding decreases with increasing the temperature effect for all samples, with different rotation speed effects. Also, it is shown that the maximum fatigue strength and life for sample B (at 1800 RPM) and the minimum fatigue strength and life for sample A (at 1600 RPM), in addition, after rotation speed 1800 RPM can be seen that the fatigue characterizations are decreased with increasing rotation speed. Fig. 15, shows that the fatigue number of cycle for friction stir welding with the effect of temperature and different rotation speeds. Also, Fig. 15. Shows the fatigue life (number of cycle) with the same behavior for fatigue strength of friction stir welding. From Figs. 13 to 15, it can be seen that the behavior of fatigue characterizations have the same behavior of tensile strength of friction stir welding, which gives the best sample is sample B (at 1800 RPM).
V. CONCLUSIONS

From the experimental and numerical investigation of friction stir welding presented to evaluate the fatigue characterization with and without temperature effect for various rotation speeds, can be summarized as follows,

1. The experimental fatigue results for friction stir welding calculated from manufacturing device is in good agreement with numerical technique by using finite element method with a maximum percentage of discrepancy is about (9.7%).
2. The increase for rotation speed lead to a decrease the strength and the fatigue characterizations for friction stir welding. Unless, the rotation speed 1800RPM give a maximum value for strength and fatigue characterizations (strength and life) for friction stir welding.
3. The acceptable value for rotation speed is 1800 RPM, which gives the maximum strength and fatigue characterizations for friction stir welding with various temperature effects.
4. The fatigue characterizations (strength and life) for friction stir welding are decreased with increasing the temperature with various rotation speeds.
ACKNOWLEDGMENT
The authors would like to express thanks for the Faculty of Engineering at University of Al- Mustansiriya –Baghdad and Faculty of Engineering-University of Kufa-Kafa, Iraq.

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