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# Study the Mechanical Properties and Numerical Evaluation of Friction Stir Processing (FSP) for 6061-T6 Aluminum Alloys

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## Abstact

Friction stir processing is a new method of changing the properties of a metal through intense, localized plastic deformation ,this process mixes the material without changing the phase (by melting or otherwise) and creates a micro structure with fine, equiaxedgrains, It is used to improve the micro structural properties of metals. In this paper , the enhancement of mechanical properties of friction stir welding specimens at variable rotation speeds (1100,1300 and 1500 rpm ) with constant feed speed(60 mm/min) for 6061-T6 aluminum alloy is studied by using the friction stir processing method at the same variable rotation speed and feed speed in order to transform a heterogeneous micro structure to a more homogeneous, refined micro structure. The best results of the weld gained at the parameter 60 mm/min weld speed and 1300 RPM rotation speed for the FSW and FSP where the efficiency reaches to 84.61% for FSW and 89.05% for FSP of the ultimate tensile strength of the parent metal .This research is developed a finite element simulation of friction stir processing (FSP) of 6061-T6 Aluminum alloy. Numerical simulations are developed for thermal conductivity, specific heat and density to know the relationship of these factors with peak temperature, The simulation model is tested with experimental results. The results of the simulation are in excellent comparison with the experimental results.

**Key words**: Aluminum Alloy (AA) , friction stir welding (FSW) , friction stir processing (FSP) , rotating speed , microstructure ,efficiency , Micro hardness .

Friction stir processing (FSP) is a new microstructural modifications technique; recently it FSP has become an efficient tool for homogenizing and refining the grain structure of metal sheet. Friction stir processing is believed to have a great potential in the field of superplasticity in many aluminum alloy (AA) [1].

FSP is a solid-state process which means that at any time of the processing the material is in the solid state.In FSP a specially designed rotating cylindrical tool that comprises of a pin and shoulder that have dimensions proportional to the sheet thickness. The pin of the rotating tool is plunged into the sheet material and the shoulder comes into contact with the surface of the sheet, and then traverses in the desired direction. The contact between the rotating tool and the sheet generate heat which softens the material below the melting point of the sheet and with the mechanical stirring caused by the pin, the material within the processed zone undergoes intense plastic deformation yielding a dynamically-recrystallized fine grain microstructure [2] as show in fig (1)

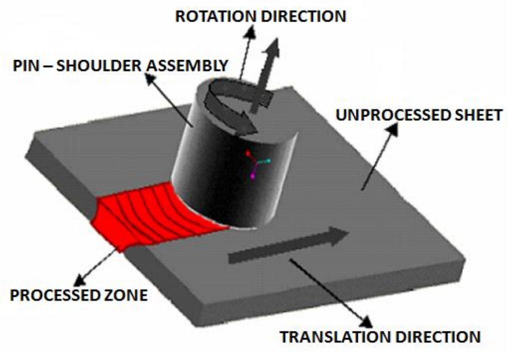


**Figure 1:** Schematic of friction stir processing (FSP) [3]

The FSW and FSP zones are (a) Base metal , No material deformation has occurred; such remote material has not been affected by the heat flux in terms of microstructure or mechanical properties.

(b) Heat affected zone (HAZ). In this region the material has undergone a thermal cycle which has modified the microstructure and/or the mechanical properties. However, no plastic deformation occurred in this area. (c) Thermo-mechanically affected zone (TMAZ). In this area, the material has been plastically deformed by the tool, and the heat flux has also exerted some influence on the material. In the case of aluminum, no recrystallization is observed in this zone; on the contrary, extensive deformation is present. (d) Nugget, the recrystallised area in the TMAZ in aluminum alloys is generally called the nugget. In such zone, the original grain and subgrain boundaries appear to be replaced with fine, equiaxed recrystallized grains characterized by a nominal dimension of few micrometers. [4] as show in fig (2)

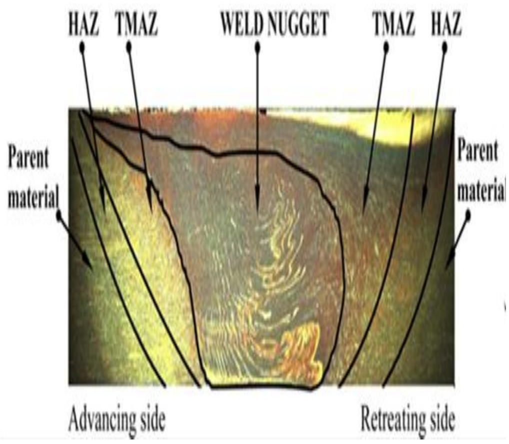


**Figure 2:** FSW and FSP zones [5]

In this study 6061-T6AA was selected, and it is selected because have high characteristics and widely applications of good characteristics and wide applications and the Characteristics of 6061 AA are: Excellent joining characteristics, good acceptance of applied coatings. Combines relatively high strength, good workability, and high resistance to corrosion, and T6 is means Solution heat treated then artificially aged [6]. And the

Applications of 6061-T6: Aircraft fittings, camera lens mounts, couplings, marines fittings and hardware, electrical fittings and connectors, decorative or misc. hardware, hinge pins, magneto parts, brake pistons, hydraulic pistons, appliance fittings, valves and valve parts; bike frames [6]

## 2. Experimental work

### 2.1 FSW and FSP Procedure

FSW and FSP procedure on the 6061-T6aluminum alloy plates 3 mm thickness, 200 mm length, and 75 mm width as show in Fig (3), a clamping fixture was utilized in order to fix the specimens to be welded on a MITSUBISHI CNC M70V milling machine Fig.(4).

And the standard mechanical properties and chemical composition of 6061-T6 AA of the present work and standard are given in Table 1 and Table 2 respectively.

**Table 1:** Mechanical properties of 6061-T6AA [6]

| | Ultimate Strength (MPa) | Yield Strength (MPa) | Modulus of elasticity (GPa) |
|---|---|---|---|
| (1) | 310 | 276 | 68.9 |
| (2) | 325.306 | 290.55 | 69.3 |

**Table 2**: Chemical Composition of 6061-T6 AA [7]

| | Mg | Si | Cr | Mn | Ti | Cu | Zn | Fe | Al |
|---|---|---|---|---|---|---|---|---|---|
| (1) | 0.8-1.2 | 0.4-0.8 | 0.04-0.35 | Max 0.35 | Max 0.35 | 0.15-0.4 | Max 0.7 | Max 0.7 | Balance |
| (2) | 0.95 | 0.65 | 0.068 | 0.055 | 0.038 | 0.34 | 0.18 | 0.57 | Balance |

Where (1): Standard , (2) :Measured

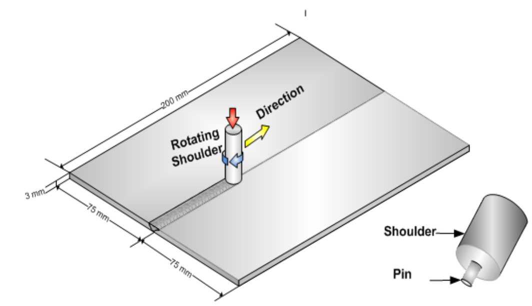


**Figure 3**: Schematic of friction stir welding (FSW) for plates


**Figure 4:** MITSUBISHI CNC M70V milling machine

The initial FSW and FSP tool designed was a simple cylindrical tool with 16 mm shoulder diameter (SD) and 5 mm pin diameter (PD) [ as SD =( 3-3.5)PD[8] ], height of the pin equal to the distance that plunged in the plate and it was 2.9 mm of the sheets processed the length of the stirrer was same as the required welding depth. The welding process was carried out by rotating the stirrer at different rotational and welding speeds under a constant friction.

The welding tool was made of tool steel X38 The tool pin is brought in contact with the work piece top surface and the tool is put into rotation using digit control part and the welding speed is controlled by the manual spindle to get the desired welds to complete FSW .

And then at the same rotation and traverse ( Feed ) speed in Table ( 4 ) return in reverse direction Until reaching the starting point for welding to produce FSP. As show in fig (5)

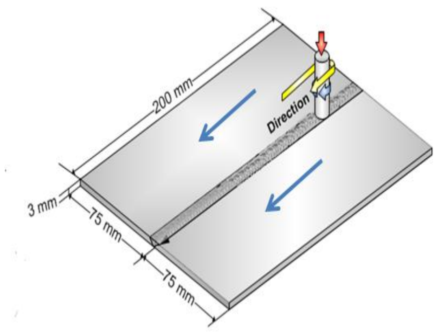


**Figure 5: FSP process for aluminum plates**

FSW and FSP is done following the conditions that are shown in Table 3.

**Table 3 :** FSW & FSP process at variable rotation speed at 60 mm/min feed speed

| Type of welding | Rotation speed (RPM) |
|---|---|
| FSW1 | 1100 |
| FSW2 | 1300 |
| FSW3 | 1500 |
| FSP1 | 1100 |
| FSP2 | 1300 |
| FSP3 | 1500 |

The specimens that needs to be testing for FSW & FSP welded has be cutting by CNC milling machine(C-TEK milling machine)

## 2.2 Sample Testing

### 2.2.1 Tensile Test

A simple tensile test was carried out using a tensile testing device , at a speed of 10 mm /min to the test specimens of 6061-T6 aluminum alloy were prepared following the ASTM **E 8M** [9] standard specimen geometry shown in Fig.6

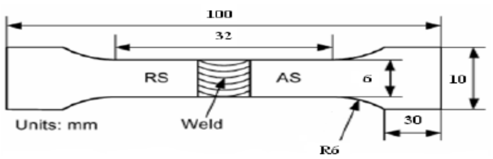


**Figure 6:** standard tensile specimen

[

And Table ( 4 ) is explain the specimens for tensile test

**Table 4 :** specimens the tensile of FSW and FSP

| Name of specimens | Type of welding |
|---|---|
| A1,A2 | FSW1 |
| A3,A4 | FSW2 |
| A5,A6 | FSW3 |
| A7,A8 | FSP1 |
| A9,A10 | FSP2 |
| A11,A12 | FSP3 |

### 2.2.2 Microstructure test

Metallographic tests were carried out using an optical microscopic at (500X) for the zooming power. The tests involved the analysis of the central area of the weld (the so-called nugget zone), the area deformed thermo-mechanically affected zone ( TMAZ ), and the heat affected zone ( HAZ ).Etching was carried out using Keller’s etchant. It is involved (2 ml HF , 3 ml HCL , 5ml HNO3 , 190 ml H2O ) according to ASTM E407-76 [10] .

### 2.2.3 Micro Hardness Test

Hardness is a quantifiable mechanical property of a material. At the microscopic level, it is a measure of resistance of the material to indentation and cracking [11].Micro hardness testing using a hardness tester is capable of providing useful information on hardness variation through different regions of the FSW & FSP plate. The hardness profiles were measured along the centerline of the cross section of the welds at about nine points (five points at the left of the weld and five points at the right of the weld and another point in the center of the weld) with various welding rotational and translational speeds using micro hardness apparatus. Fig. 7 shows the micro hardness apparatus: The specimens are presented in Fig. 8.

**Figure 7:** Micro hardness tester

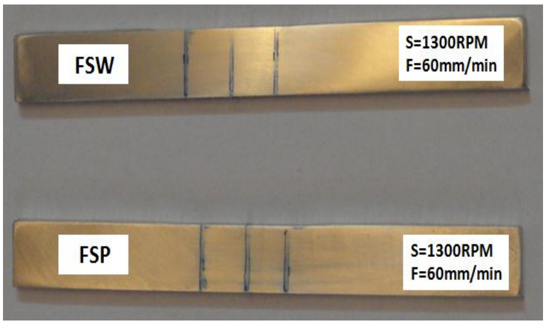


**Figure 8:** Hardness test specimens

### 2.2.4 Radiographic Test

X-ray is the employing radiographic test to penetrate an object and detect any discontinuities by the resulting image on a recording or viewing medium The medium can be photographic film is D4 as the film type is the sensitized paper , a fluorescent screen (the result here was a viewing medium) the source energy is supplied to welded plates is 150kv and 2.2mA is current for 3mm thickness according to ASTM 1A/SWSI [12 ].Fig.9 illustrates the X-Ray examination system**.**


**Figure 9:** X-Ray examination system

### 2.2.5 Thermal Modeling

The objective of FSP modeling is to simulate welding process using finite element approach (ANSYS 14.5 program) to obtain temperature distribution on welded plate (sheets) and to calculate the heat input during welding process depending on assumed maximum temperature. Another objective of FSP modeling is to propose a method to calculate force required for welding process.

In the present thermal analysis, the workpiece is meshed using a brick element called SOLID70. This element has a three-dimension thermal conduction capability and can be used for a three-dimensional, steady-state or transient thermal analysis. The element is defined by eight nodes with temperature as single degree of freedom at each node and by the orthotropic material properties.

In order to simplify the moving tool on the sheet welded line in ANSYS program , all next steps were made to make it like moving tool along welded line in the ANSYS program.

To get a good accurate of results, more steps of shoulder area must be made in the simulation of program as shown in Figure 10

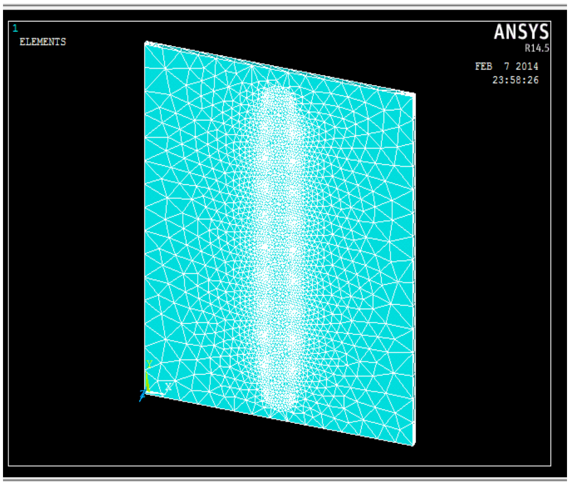


**Figure 10:** Steps of circular shoulder area along welded line.

Where each shoulder circle has heat generation and time step, each circle represents one step.

The thermal modeling was carried out. Transient thermal analysis is the stage. Fig(11) illustrates the flow diagram of the method used for the finite element analysis.

In order to simplify the moving tool on the sheet welded line in ANSYS program , all next steps (as shown in flow chart) was made to make it like moving tool along welded line in the ANSYS program.

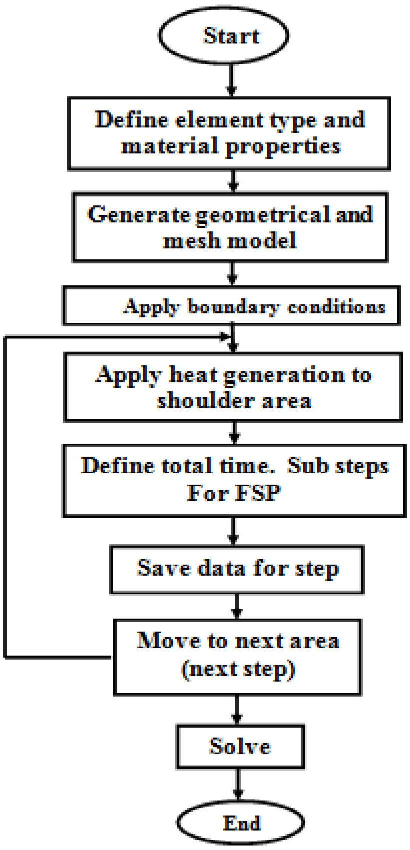


**Figure 11**: Flowchart of thermal modeling.

For practice part has been measured temperatures for 6061-T6 aluminum alloy using thermal Imaging camera shown in fig (12)


**Figure 12:** Thermal Imaging Camera

and has been selected one point for testing in the same dimensions for two alloys as shown in fig ( 13) and the results of temperatures were recorded to the ram of thermal imaging camera to explain the relationship between temperature and time.

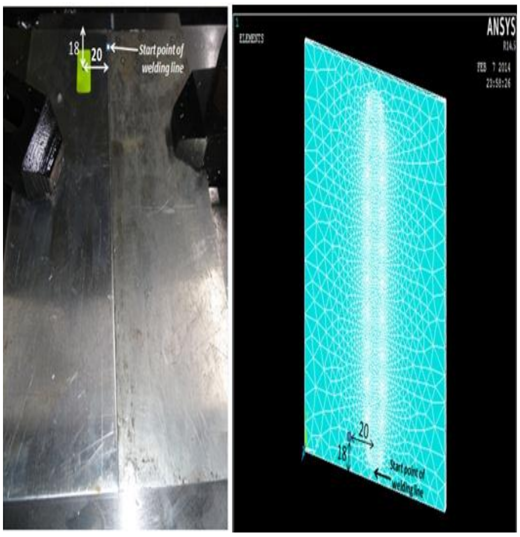


**Figure 13: Node Location for Practical and Theoretical**

And in this test to clarify the comparison between the results of the practice results by thermal camera and the theoretical results by ANSYS program.

## 3. Results and Discussions.

Experimental results for6061-T6 aluminum alloys are welding by FSW and FSP in this paper. The most common measure of FSW and FSP quality after welding were done in (tensile, Micro hardness, microstructure, and X-Ray) tests.

## 3.1 FSW and FSP Results

The friction stir welding (FSW and FSP) joints are shown in Fig. 14 and fig. 15

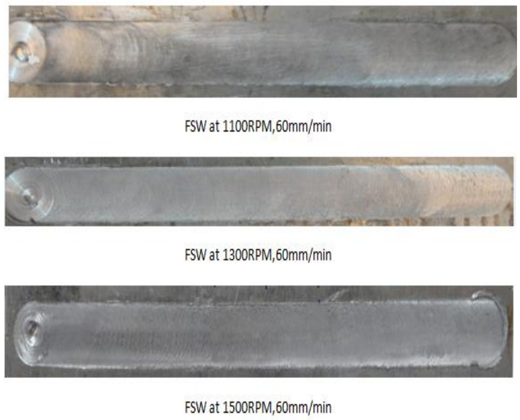


**Figure 14:** The appearance of upper surface of welding beads of 6061-T6AA plates produced by FSW.


**Figure 15:** The appearance of upper surface of welding beads of 6061-T6AA plates produced by FSP.

For these figures (14 and 15) all welding lines are have good appearance by visual inspection

### 3.2 Tensile Results

Fig (16) show the values of ultimate tensile strength of welded specimens and ultimate tensile strength of base metal

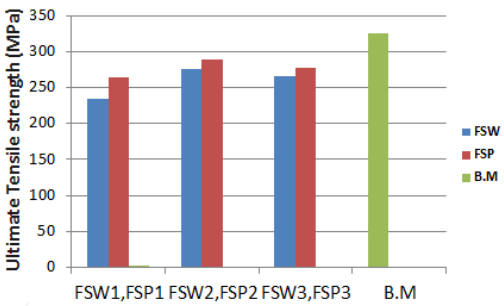


**Figure 16:** Ultimate Strength Results Results for 6061-T6

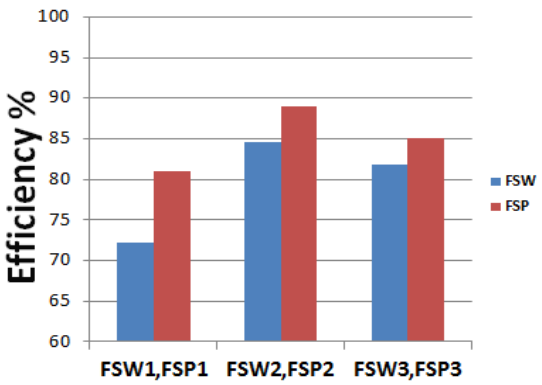


**Figure 17**: Shows The Efficiency For Each Case Compare With Base Metal

The optimum value of ultimate strength for 6061-T6 was obtained at 1300 rpm rotating speed and 60 mm/min welding speed for both FSW & FSP , it was 275.253MPa and 84.61% for FSW and 289.694 MPa and the welding efficiency is 89.05% for FSP of the base metal , FSP method is effective, it will give long life welds because of FSP is enhance the mechanical properties and modification of microstructure is leads to increase the mechanical properties.. The tensile strength of the joint is little lower than that of the parent metal [13] . The efficiency of the FSP process is the highest of all other welding processes such as ( TIG , MIG ) For instance the efficiency for welded 6061-T6 AA by TIG process equal between ( 50-60 % ) [14].

### 3.3 Microstructure results

The optimum resulted from tensile test are both in FSW & FSP are examined in microstructure test and fig ( 18 ) are explain the microstructure of welding zones in both cases

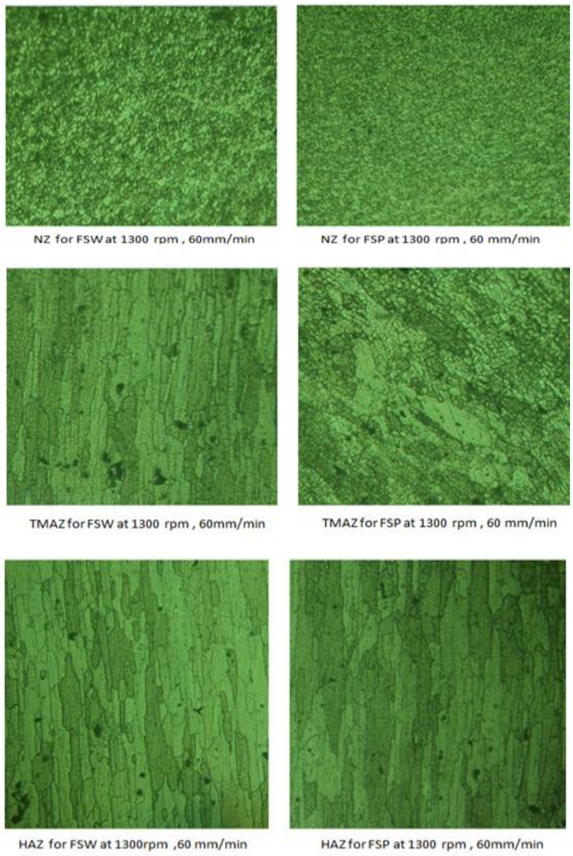


**Figure 18:** The microstructure of welding zones in FSW & FSP

the welding zones consists of three zones: the nugget zone (NZ ), the thermo mechanical affected zone (TMAZ), and the heat affected zone (HAZ).the grain size distributions are shown, and it is obvious that grain size within the nugget region is much smaller than that of other regions and the diameter of grain size for NZ 6061-T6 equaled 4.5 µm and 3.5 µm for

FSW and FSP of alternatively, the FSP is ultra fining and modification of microstructure for nugget(welding ) zone and other welding zones this refining leads to increase the mechanical properties and this microstructure is proved are no porosity or defect in welding ( Nugget) zone in both cases.

## 3.4 Micro hardness results

Hardness profiles are extremely useful, as they can assist in the interpretation of the weld microstructure and mechanical properties. Each specimen was tested by dividing it into regions each point took 10 seconds in hardness Vickers (HV) then the reading has been recorded and measured the other points respectively were measured. when the distance between any two points is 2 mm. The results for FSW and FSP at 1300 RPM and 60 mm/min for 6061-T6 are presented in Fig (19)

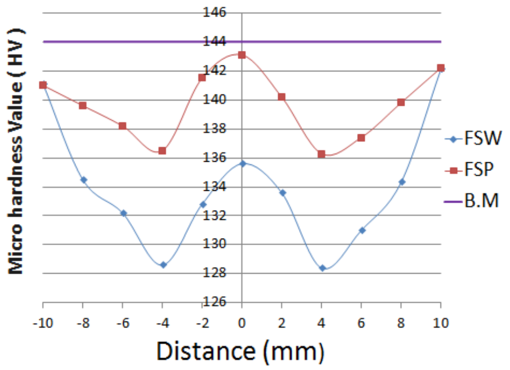


**Figure 19:** Hardness profiles of FSW and FSP

From fig (19) the hardness varied at different positions of the processed area. The hardness profile shows that the hardness values at the center of the deformation zone (nugget zone) is higher than the other zones, and as going farther from the nugget the hardness decreases till it reaches its minimum value at edge of the deformation zone (heat affected zone) and then increases again [15]. Friction stir welding is caused to decreasing of the displacement density and de-creasing in that cause to decreasing of the micro hardness. In this process tool rotation and feed rate cause to dynamic recristallization and dynamic recristallization cause to new grain giant [15]

The results show in this figures that the friction stir processed area has a higher Vickers hardness value than friction stir welded.

The nugget the hardness decreases till it reaches its minimum value at edge of the deformation zone (heat affected zone) and then increases again [16]. And for fig(24) is explain the values of Vickers hardness for FSW and FSP and this fig distinguished the increase of .hardness in FSP because the FSP is leads to refining of microstructure and enhancement of mechanical properties.

## 3.5 X-Ray Radiographic Results

6061-T6 AA welded plates by FSP plates were examined by x-Ray that the welded region is avuncular of welding defects and the result is represented in Fig20


**Figure 20:** X-Ray Radiographic for FSP of 6061-T6AA at 1300 rpm, 60 mm/min.

## 3.6 Results of numerical modeling of friction stir processing ( FSP )

Experimental results of friction stir Processing (FSP) of 6061-T6 Aluminum alloys were compared with simulation results of ANSYS program at point A. The welded work piece had dimensions of (150 ×200 ×3) mm, the tool had a shoulder radius of 8 mm, pin radius of 3 mm and pin length of 2.9 mm. The rotation speed and Feed speed that were utilized in this comparison were 1300 RPM and 60 mm /min for 6061-T6 .

440 seconds is the total time is required to complete the FSP for 6061-T6 AA .
440 seconds is the total time is required to complete the FSP for 6061-T6 AA .

Figures (21) show how to exhibiting a certain results of the readings temperature for variable periods time for the same point of two welded alloys by thermal imaging camera.

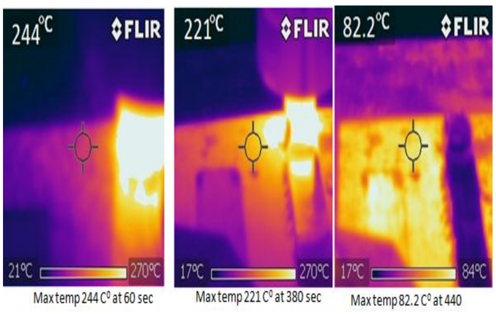


**Figure 21:** Some Reading Temperatures Of FSP For 6061-T6

Fig (22) below show the results that are calculated experimentally and simulation results.

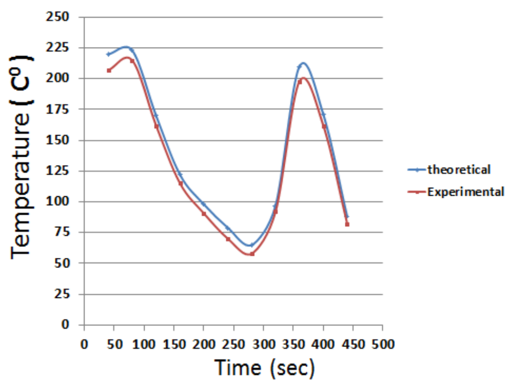


**Figure 22:** Temperature Distribution Point A For FSP Of 6061-T6

The modeling of this work is solved and the temperature distribution obtained for the model and the result show that there is very good agreement between present work and ANSYS result. But there is simple different in results with calculation temperature distribution between experimental examination and modeling ranging between 4 – 9 % .

Figure (23) to (25) show the maximum temperature of welding plate which has been reached at several time steps:

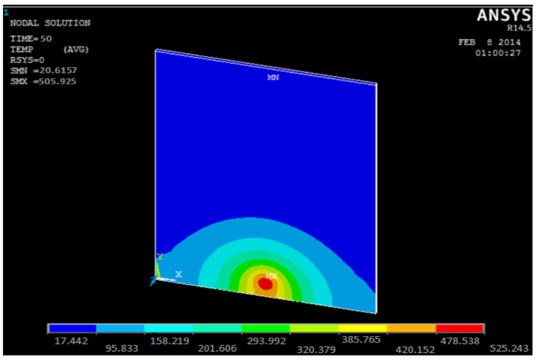

**Figure 23:** Temperature distribution of 6061-T6 AA plate at step 50second, maximum temperature is 505.925C $^{0}$.

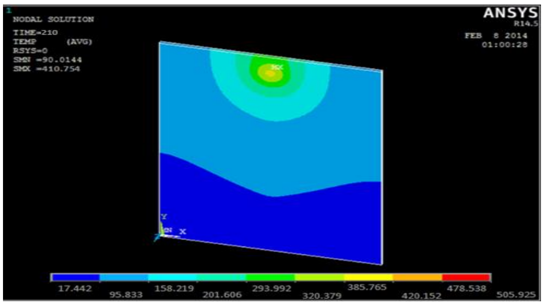

**Figure 24:** Temperature distribution of 6061-T6 AA plate at step 210 second, maximum temperature is 410.754C $^{0}$.

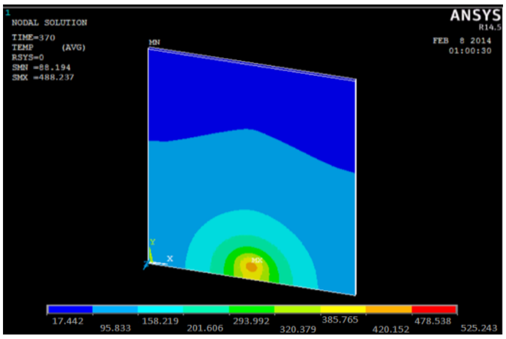

**Figure 25:** Temperature distribution of 6061-T6 AA plate at step 370 second, maximum temperature is 488.237C $^{0}$.

## 4. Conclusion

1. Welding of 6061-T6 Al-alloys by Friction stir processing is better than friction stir welding at the same rotating and feed speed.
2. The best efficiency of joints of the used parameters of FSW and FSP for 6061-T6 were founded at 60 mm/min weld speed and 1300 rpm rotation speed, it reaches efficiency of (84.61 and 89.05 %) of the ultimate tensile stress of the base metal for FSW and FSP respectively.
3. The micro hardness values were variable from weld line distance due to change in micro structural properties.
4. The friction stir processing is improved the micro structural properties at welding zones especially nugget zone and it caused grain refined.
5. The X-ray test showed the welding line for 6061-T6 Aluminum Alloy is absence of any type of defects.

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# دراسة الخواص الميكانيكية والمحاكاة العددية لسبائك الالمنيوم من نوع 6061-T6 الملحومة بطريقة المعالجة بالمزج الاحتكاكي.

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**الخلاصة:**

تعتبر طريقة معالجة المزج الاحتكاكي من الطرق الحديثة لتحسين خصائص المعادن في هذه العملية يتم مزج المواد دون إي تغيير في الأطوار (عن طريق انصهار أو غير ذلك) و يتم استخدام تلك الطريقة لتحسين خصائص البنية المجهرية للمعادن.

في هذه الدراسة ، تم قياس الخواص الميكانيكية لعينات لحام المزج بالاحتكاك بسرعات متغيرة وهي ((1700,1500,1300 دورة في الدقيقة ) مع سرعة تغذية مقدارها ( 60 ملم/ دقيقة ) و من ثم تم استخدام طريقة المعالجة بالمزج الاحتكاكي لنفس سرع الدوران وسرعة تغذية المستخدمة في اللحام بالاحتكاك من أجل تحسين الخواص الميكانيكية لسبائك الالمنيوم من نوع 6061-T6و تحويل البنية المجهرية إلى بنية مجهرية أكثر تجانسا.

وكانت أفضل نتائج لخط اللحام عند سرعة خطية مقدارها 60 ملم / دقيقة و سرعة دوران 1300دورة / دقيقة وكانت الكفاءة مقدارها84.61 ٪ و 89.05 ٪ بالنسبة للحام المزج بالاحتكاك ومعالجة المزج الاحتكاكي على التوالي و قد تم حساب الكفاءة اعتمادا على أقصى مقاومة شد للقطع الملحومة مقارنة مع أقصى مقاومة شد للمعدن الأساسي , وتم أيضا دراسة تأثير طريقة معالجة المزج الاحتكاكي على تحسين البنية المجهرية وزيادة مقدار الصلادة المجهرية لسبائك الألمنيوم من نوع 6061-T6 الملحومة بطريقة اللحام بالمزج الاحتكاكي وأيضا تم فحص أفضل النتائج التي تم الحصول عليها بفحص الأشعة السينية واظهر هذا الفحص خلو العينات المفحوصة من إي نوع من أنواع العيوب .

هذا البحث تضمن تطوير طريقة الجزئيات المحددة لمعالجة المزج الاحتكاكي لسبائك الألمنيوم من نوع 6061-T6. وتم اختبار نموذج المحاكاة بين النتائج التجريبية عن طريق كاميرا التصوير الحراري والنتائج العددية عن طريق برنامج (ANSYS 14.5) الذي يتم من خلال إعطاء الموصلية الحرارية، والحرارة النوعية والكثافة لمعرفة علاقة هذه العوامل مع درجة الحرارة الذروة ونتائج المحاكاة وأظهرت مقارنة جيدة مع النتائج التجريبية.