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# Comparative Investigation of Friction Stir Welding and Tungsten Inert Gas of 6061T651 Aluminum Alloy on Mechanical Property and Microstructure

**Samer Jasim Mahmood**
Engineering College, University of Nahrain / Baghdad
Email: samerjasem@yahoo.co.uk

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## ABSTRACT

This study has been conducted to investigate the effect of welding process parameter on the mechanical properties and microstructure of aluminum alloy 6061, using friction stir welding (FSW) and Tungsten inert gas welding (TIG). Different friction stir welded specimens were produced by employing variable welding speed from 10 to 40 mm/min, and constant rotation speed at 900 rpm. Different mechanical tests and microstructure examination were performing to evaluate the joints. The experimental results indicate that the welding process parameters have significant effect on mechanical properties of the joints, the best result of the (FSW) weld achieve at 30 mm/min welding speed which give tensile strength 189 MPa, and 55% joint efficiency of the ultimate tensile strength of parent metal. Tungsten inert gas welded (TIG) give tensile strength 124 MPa with 37% efficiency of the ultimate tensile strength of parent metal. The profile of micro hardness tests is shown variation in the hardness through the welding zones the lowest value at heat affected zone which is 60 HB and the highest value at the nugget zone which is 80HB, but in the case of Tungsten inert gas welded (TIG) the micro hardness profile is constant though the welded zones and the value of the hardness is very low about 43. The microstructure examinations of the friction stir – welded (FSW) are shown three welded zones, first fine equated crystalline in the nugget zone, second highly elongated grain with very small cells in thermo mechanical affected zone and third slightly elongated coarse grain in heat affected zone. For Tungsten inert gas welding (TIG) the microstructure contain dendrite structure with black eutectic regions and significant amount of aluminum and silicon.

**Keywords:** Friction stir and TIG welding; Aluminum alloy.



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2412-0758/University of Technology-Iraq, Baghdad, Iraq

# دراسة مقارنة البنية المجهرية والخواص الميكانيكية لوصلات لحام التنكستن(TIG) ولحام الاحتكاك والخلط , (FSW) لسبيكة الالمنيوم 6061T651


**الخلاصة**

اجريت هذة الدراسة لمعرفة تاثير ضروف اللحام على الخواص الميكانيكية والمجهرية لسبيكة الالمنيوم 6061T651 وذلك باستخدام اللحام بالاحتكاك والخلط (FSW) ولحام التنكستن(TIG) .عينات لحام احتكاك وخلط مختلفة انتجت من خلال توضيف سرع لحام متغيرة من ١٠ الى ٤٠ ملم بالدقيقة وسرعة دورانية ثابتة ٩٠٠ دورة بالدقيقة وقد اجريت اختبارات ميكانيكية مختلفة وفحص البنية المجهرية لتقييم اداء وصلات اللحام . النتائج العلمية تشير الى ان ظروف اللحام لها تاثير كبير على الخواص الميكانيكية للوصلات .افضل نتيجة للحام الاحتكاك والخلط تحققت في سرعة خطية ٣٠ ملم بالدقيقة والتي اعطت مقاومة الشد ١٨٩ ميكا باسكال و كفاءة لحام ٥٥% من مقاومة الشد النهائي للمعدن الاساس.لحام التنكستن اعطى مقاومة شد ١٢٤ ميكا باسكال وكفاءة ٣٧% من مقاومة الشد النهائي للمعدن الاساس.اضهر اختبار الصلادة المجهرية تغير الصلادة خلال مناطق اللحام و ادنى قيمة في منطقة التاثير الحراري والتي تبلغ ٦٠ صلادة برنيل واعلى قيمة في منطقة اللحام والتي تبلغ ٨٠ صلادة برينيل,لكن في حالة لحام التنكستن تكون الصلادة المجهرية ثابتة خلال مناطق اللحام وتكون قيمة الصلادة منخفضة جدا حوالي ٤٣ صلادة برينيل.واضهرت اختبارات البنية المجهرية للحام الاحتكاك والخلط ثلاث مناطق لحام,الاولى بلورات ناعمة ومتساوية في منطقة اللحام ,الثانية بلورات مشكلة طوليا مع خلايا صغيرة جدا في منطقة التاثير الميكانيكي والحراري, الثالثة بلورات خشنة طوليا قليلا" في منطقة التاثير الحراري وتحتوي البنية المجهرية للحام التنكستن على بنية شجيرية مع مناطق سوداء سهلة الانصهار و كمية كبيرة من الالمنيوم والسليكون.


## INTRODUCTION

Friction stir welding (FSW) is a new solid-state welding method developed by The Welding Institute (TWI) in 1991**[1]**. The basic process involves in rotating a tool consisting of a cylindrical shoulder and a pin. The tool is plunged into the weld line till the shoulder makes contact with the plate surface. Once the material is sufficiently heated due to friction, it reaches plastic stage. The tool then traverses along the weld line and the plasticized material is extruded past the rotating pin, while constrained between the shoulder and the backing plate thus forming the joint. As FSW is a solid state joining technique, it is particularly suited for joining high strength aluminum alloys, which were previously considered as unweldable by fusion welding techniques **[2]** In TIG welding, an electric arc is formed between an inconsumable tungsten electrode and the workpiece. The arc provides the thermal energy to melt the workpieces as well as the filler if necessary. For Al alloys, due to their elevated thermal conductivity, the weld penetration remains very shallow: less than 3mm in one pass. To enhance the penetration, activated TIG technique (TIG) is used. TIG process is a TIG modification where a coating, composed of oxides or halides, is applied on the top surface adjacent to the weld joint before welding **[3]** FSW has several advantages over the commonly used fusion welding techniques. Following from its relatively low process temperature, below the melting point, the method is suited for joining thin or difficult to weld materials. With no melting, the cast microstructure formed during conventional fusion welding is avoided as well as the weld zone shrink from solidification. Furthermore, there is limited risk for porosity in the weld zone, which is common in fusion welds. The FSW joint is created by friction heating with simultaneous severe plastic deformation of the weld zone material. The stirring of the tool minimizes the risk of having excessive local amounts of inclusions, resulting in a homogenous and void-free weld. Since the amount of heat supplied is smaller than during fusion welding, heat distortions are reduced and thereby the amount of residual stresses. The deformation control is therefore easier **[4]**. Bo Li, Yifu Shen **[5]** studded focused on the relationship between primary friction stir welding process parameters and varied types of weld-defect discovered in aluminum 2219-T6 friction stir butt-welds of thick.

Ratnesh K. Shukla**[6]** studied microstructure, micro hardness distribution, tensile properties and fracture surface morphology of weld butt joints of 6061 T6 aluminum alloy. Two different welding processes have been considered: a conventional tungsten inert gas (TIG) process and an innovative solid state welding process known as friction stir welding (FSW) process .Juan Zhao, Feng Jiang **[7]** studded the effect of weld by FSW and TIG welding on mechanical properties of Al–Mg–Sc alloy. The aim of this study is to compare the mechanical properties and microstructure of TIG and FSW joints of 6061 aluminum alloy**.**

## EXPERIMENTAL WORK

### Material

The 6000 group of aluminum alloys contain magnesium and silicon as major alloying elements and widely used for automotive and aerospace structures due to their good extrudability, weldability and excellent corrosion resistance, These alloys are also age hardenable, and usually heat treated to T6 condition (solution treatment and artificially aging) in order to develop adequate strength. Aluminum 6061 is a typical alloy of this group and contains Mg–Si alloying elements. It is used both in T4 (solution treatment and naturally aging) and T6 (Peak aging) temper conditions **[8]**.
Materials used in this study were Al6061 T651 Alloy in the form of 6 mm thick plates. Chemical compositions of the materials used are given in Table (1).and T651solution heat-treated and artificially aged.

**Table (1) Chemical composition (wt. %) of Al6061alloy.**

| Chemical composition wt.% | | Mg | Si | Fe | Ti | Zn | Cr | Cu | Mn | Al |
|---|---|---|---|---|---|---|---|---|---|---|
| Material type | ٦٠٦١ Aluminum alloy (Standard ASM)[9] | 0.8-1.2 | 0.4-0.8 | 0-0.7 | 0-0.15 | 0-0.25 | 0.04-0.35 | 0.15-0.4 | 0-0.15 | Bal |
| | ٦٠٦١ | 0.2 | 0.8 | 0.5 | _ | _ | _ | 0.3 | 0.07 | Bal |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Aluminum alloy (Measured)** | | | | | | | | | |

**Welding Processes.**

The plates of 6061 T651 aluminum alloy were cut and machined to the required size (200 mm *100 mm * 6 mm) by power hacksaw cutting and milling machine. Two different welding methods, FSW and TIG, were employed. Both FSW and TIG joints were made with the welding direction perpendicular to the rolling direction of the sheet. A series of welds were produced using friction stir welding tool Shown in Figure(1), quantitative information is in Table (٢). The friction stir welding process is shown in Figure(2). A single pass partial penetration weld using constant tool rotation speed 900 rpm and three different welding speeds (10, 20, 30 and 40 mm/min).

**Figure (1) Photograph Picture of friction stir welding tool.**

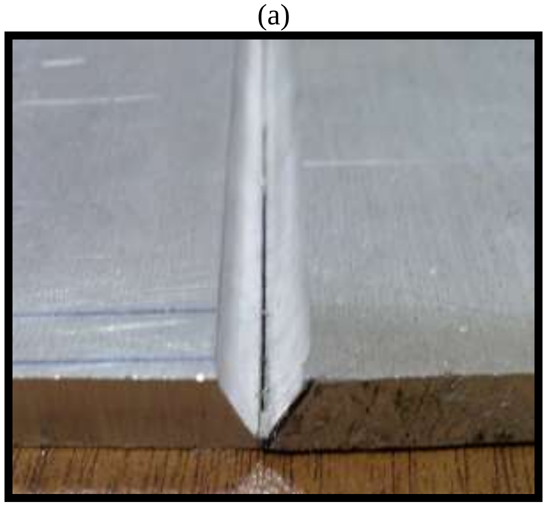
**Table (2) Details of the FSW Tool**.

| **Tool Feature** | **Tool Details** |
|---|---|
| Shoulder Diameter (mm) | 18 mm |
| Concavity | 0 |
| Probe Diameter (mm) | 5 mm |
| Probe Length (mm) | 5.5 mm |
| Chemical Composition (wt. %) | SS434<br>0.43%Si,0.47%Mn,16.6%Cr,0.4%Ni,0.7%Mo, |
| Coating | None |

**Figure (2) friction stir welding process.**

TIG joints have been realised with filler material see Figure (3a), with a Ac arc-welding power source with a 360V input and an air-cooled internal transformer. Detailed parameters are: voltage10V, welding current 157–158A, argon as shield gas, electrode WP 1.60mm × 1.75mm 4043 filler metal. The rolled plates of AA6061 T651 aluminum alloy were machined to the required dimensions (200mm*100 mm*6mm). ‘V’ butt joint configuration, as shown in Figure (3b), was prepared to fabricate TIG welded joint.

(a)



**(b)**

**Figure 3 (a) TIG welding process, (b) V butt joint.**

**Microstructure analysis and hardness measurements**

The specimens have been cut perpendicularly to the weld line for microstructure examination, where different grit sizes of sic sandpaper (400, 600, 800, 1000 and 1200) were used. Consecutively, specimens were cleaned by water after each grinding steps, alumina (aluminum oxide) was used as a polishing abrasives liquid, a good drying after washing was done for the specimens, the microstructure constituents of the specimen were revealed by using a suitable chemical etching (1.0mlHF+2.5mlHNO3+1.5mlHcl+95 ml H2O) for 10 second.

**Tensile test**

The tensile test was carried out by WDW 200 testing machine. Specimen dimensions were chosen according to the standard ASTM (B557M-84) **[10]**. The dimensions of the tensile test specimens are shown in Figure (4).

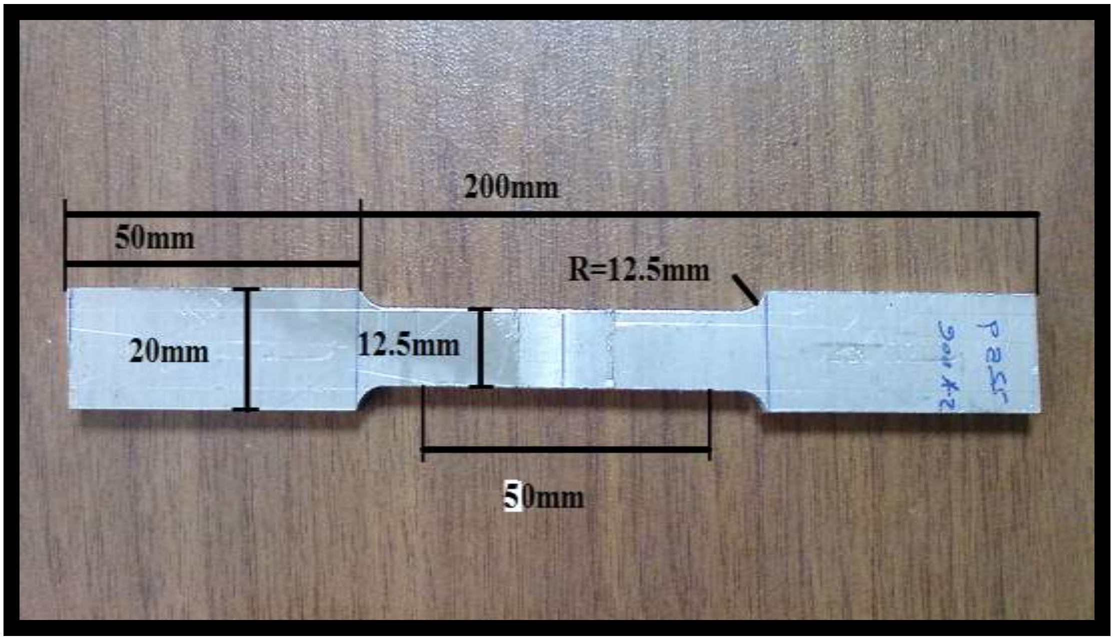



**Figure (4) Dimensions of tensile test specimens.**

## RESULTS AND DISCUSSIONS

### Hardness

Brinell hardness was measured with a 500 kg load /10mm ball indenter, hardness profiles plotted on Figure(5) demonstrate that the centre of the joints is the weakest zone of the welded structures. The hardness decrease is much smaller in FSW nugget compared to TIG molten zone. Considering that base metal hardness is around (90-95) HB, this decrease is around 11HB in the case of FSW and almost 52HB in the case of TIG. For FSW hardness drops in the heat affected zone (HAZ) due to dissolution (and growth) of precipitates. A minimum 70 HB is reached around the weld/HAZ. The TIG welded specimens have a larger hardness decrease in the weld than FSW due to welding heat and the usage of lower hardness filler metal. The minimum hardness is 43 HB on the weld centre. The hardness decreases at the beginning of the HAZ followed by a small increase and after that another decrease in the area closest to the joint line. The hardening effect in the zone within the HAZ bordering the fusion zone is due to age hardening, since hardness measurements were made some time after the production. In addition to this, different values of hardness in the base metal of the two case because of the amount of heat transmitted from the area of welding to the base metal where be higher in fusion welding, causing a decrease hardness of the base metal.

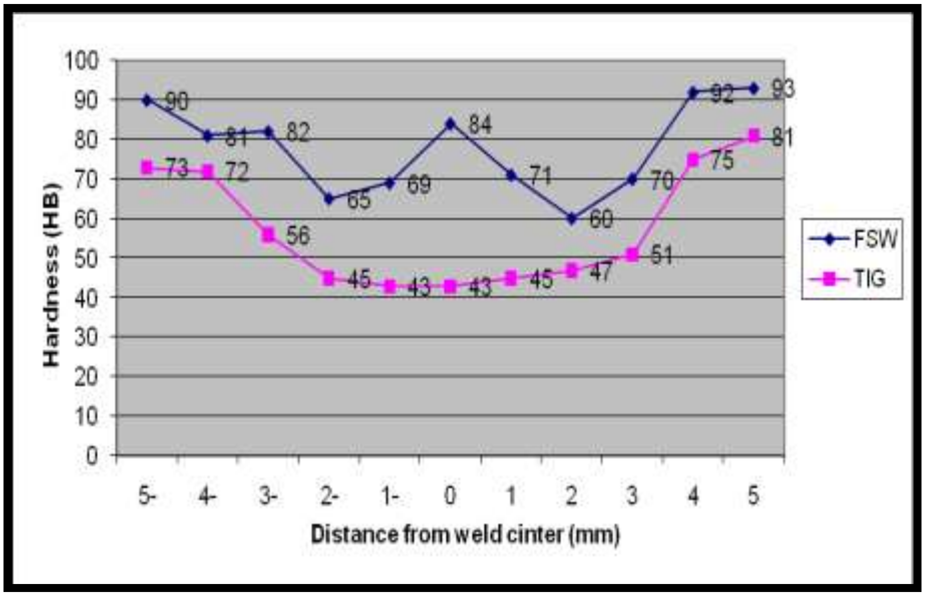


**Figure (5) hardness results of FSW and TIG welding.**

**Tensile Test**

The tensile test properties such as yield point, percentage of elongation, tensile strength of 6061 aluminum alloy joints were evaluated. Three specimens were tested; the tensile strength of unwelded parent metal is 340 MPa see Figures (6). However, the tensile strength of TIG joint is 124 MPa see Figures (7). This indicates that there is a 63% reduction in strength values due to TIG welding. Similarly, the tensile strength of FSW joints for the four welding speeds (10, 20, 30 and 40 mm/min) are (63,130,189,145 MPa) see Table (3) .The highest tensile strength occurred with the 30 mm/min welding speed Figure (8). Of the two types of welded joints, the joints fabricated by FSW exhibited a relatively higher joints efficiency (55%), and the joint fabricated by TIG exhibited a relatively lower joint efficiency is 37%.

**Table (3) the tensile strength of the weld joints.**

| Weld Type | welding speed (mm/min) | tensile strength (MPa) | Joint Efficiency in term of tensile strength (%) |
|---|---|---|---|
| PM | -- | 340 | -- |
| FSW | 10 | 63 | 19 |

| | | | |
|---|---|---|---|
| FSW | 20 | 130 | 38 |
| FSW | 30 | 189 | 55 |
| FSW | 40 | 145 | 42 |
| TIG | -- | 124 | 37 |

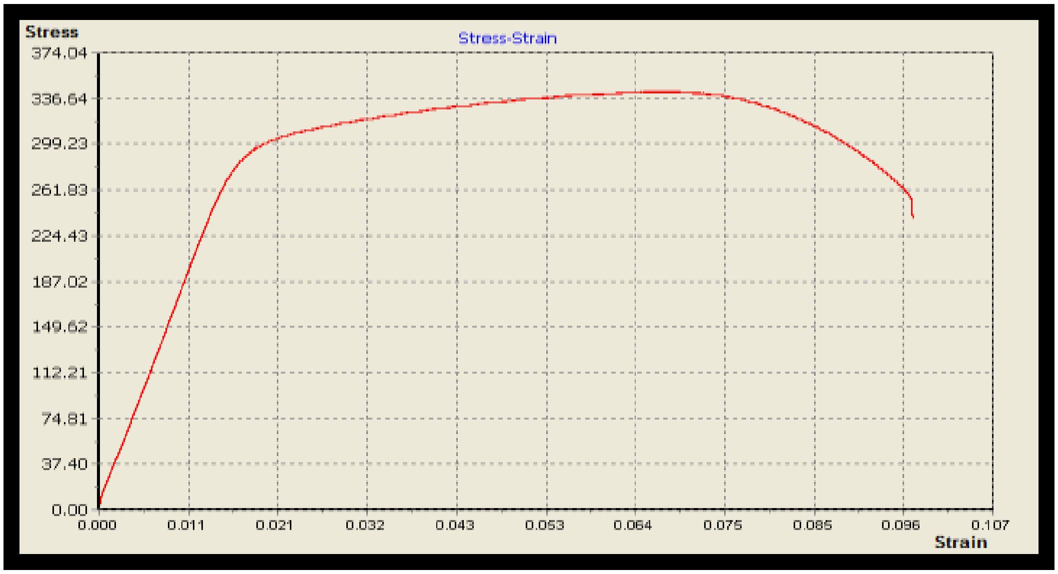



**Figure (6) stress- strain curve for unwelded parent metal.**

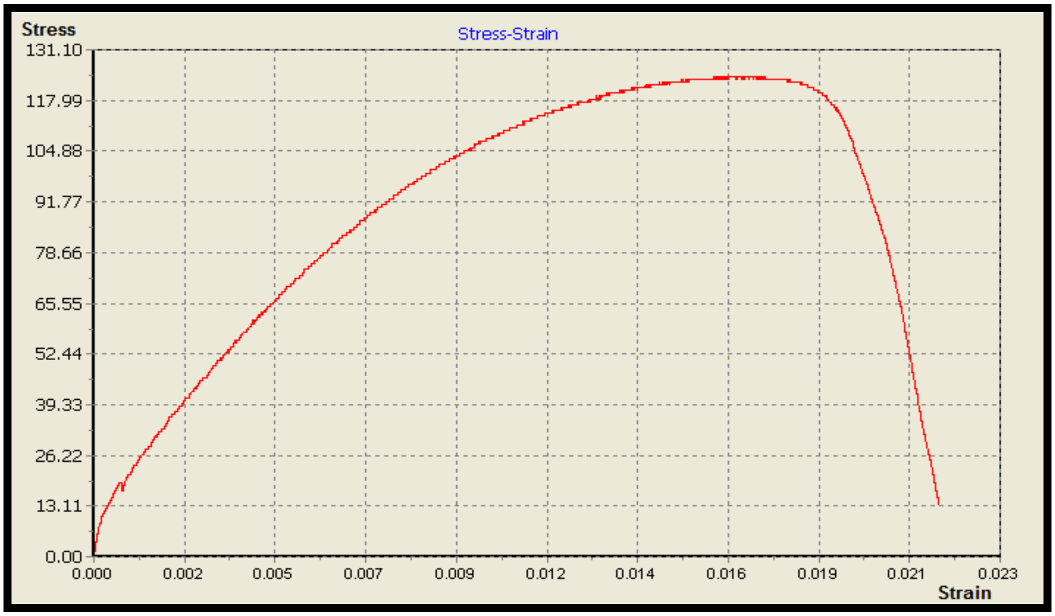



**Figure (7) stress- strain curve for TIG joint.**

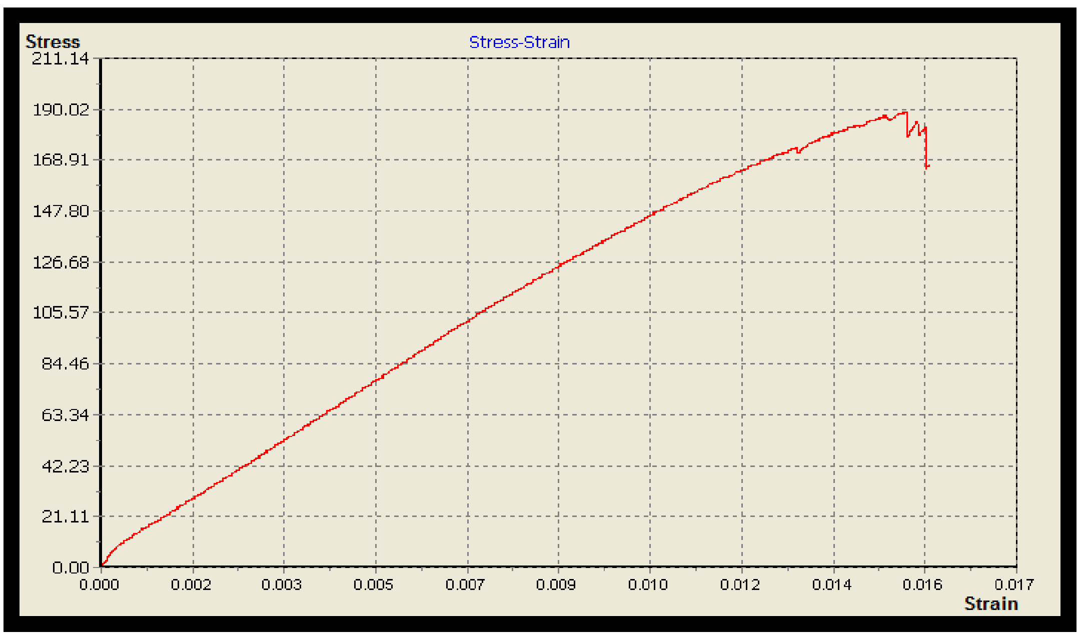



**Figure (8) stress- strain curve for FSW joint.**

## Microstructure Results

Microstructure of the joints was examined at different locations, but most of the tensile specimens failed in the weld metal region, and the optical micrographs taken at the weld metal region for comparison purpose see Figure (9) Microstructure of 6061T651 Aluminum Alloy. In friction stir welding the grain structure can be divided in to several major zone Figure (10): (i) fine equated crystallites in the nugget at the weld center nugget zone NZ (ii) highly elongated grain with very small cells retreating and advancing side thermo mechanical affected zone TMAZ,and (iii) slightly elongated coarse grain in the heat affected zone (HAZ) and base metal (BM).in microstructures of Al6061 alloy in as-welded condition are shown in Figure(11) .

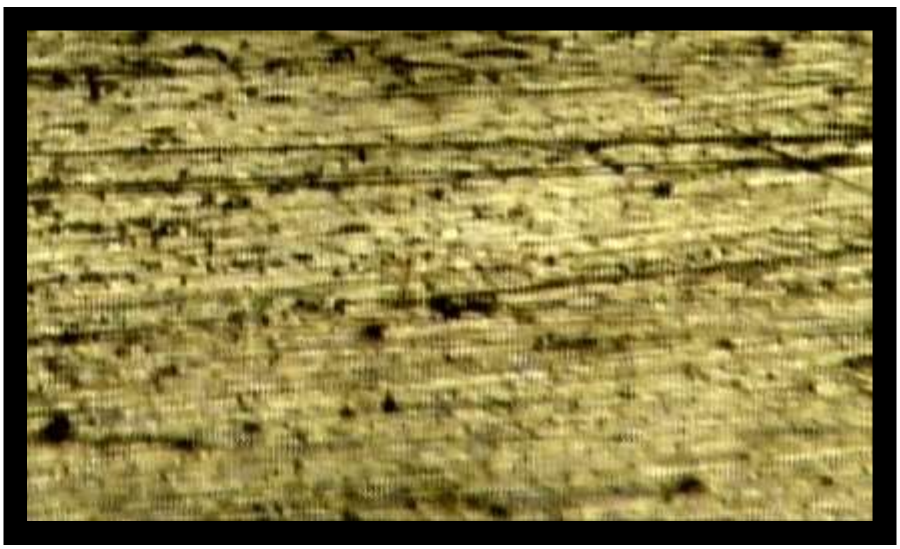


**Figure (9) Microstructure of 6061T651 Aluminum Alloy.**

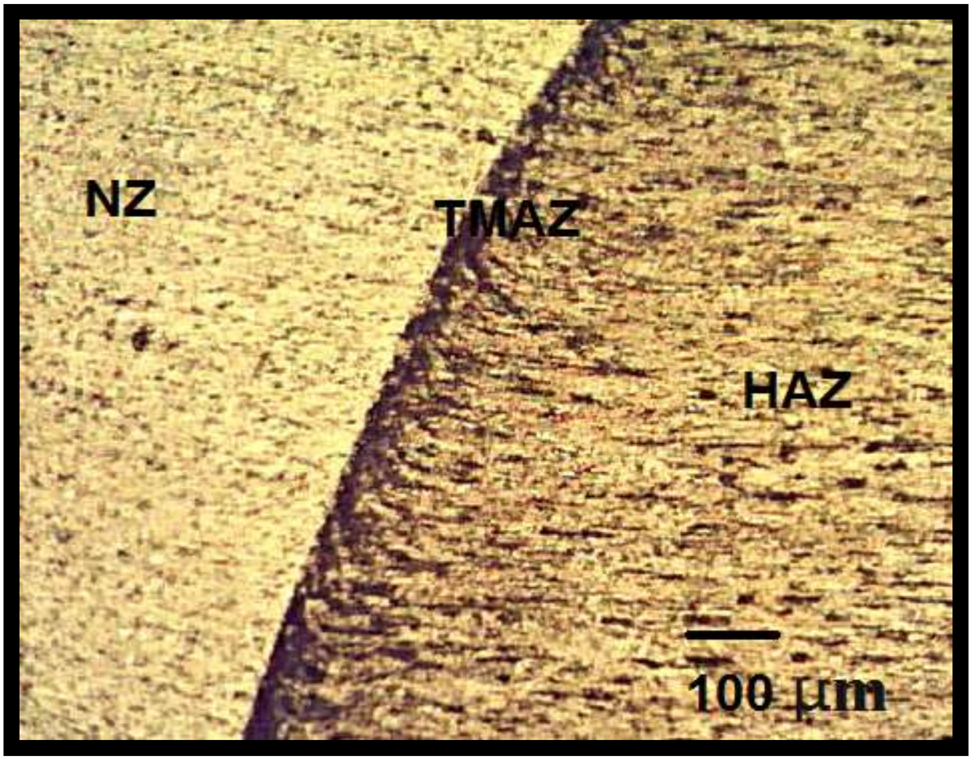



**Figure (10) Microstructure of FSW joint.**

The fusion zone of TIG joints Figure (10) contain dendrite structure and this may be due to the fast heating of base metal and fast cooling of molten metal due to welding heat. It is obvious that black eutectic regions consist of significant amount of Al and Si. As 4043 filler metal consists of 5 wt. % silicon.

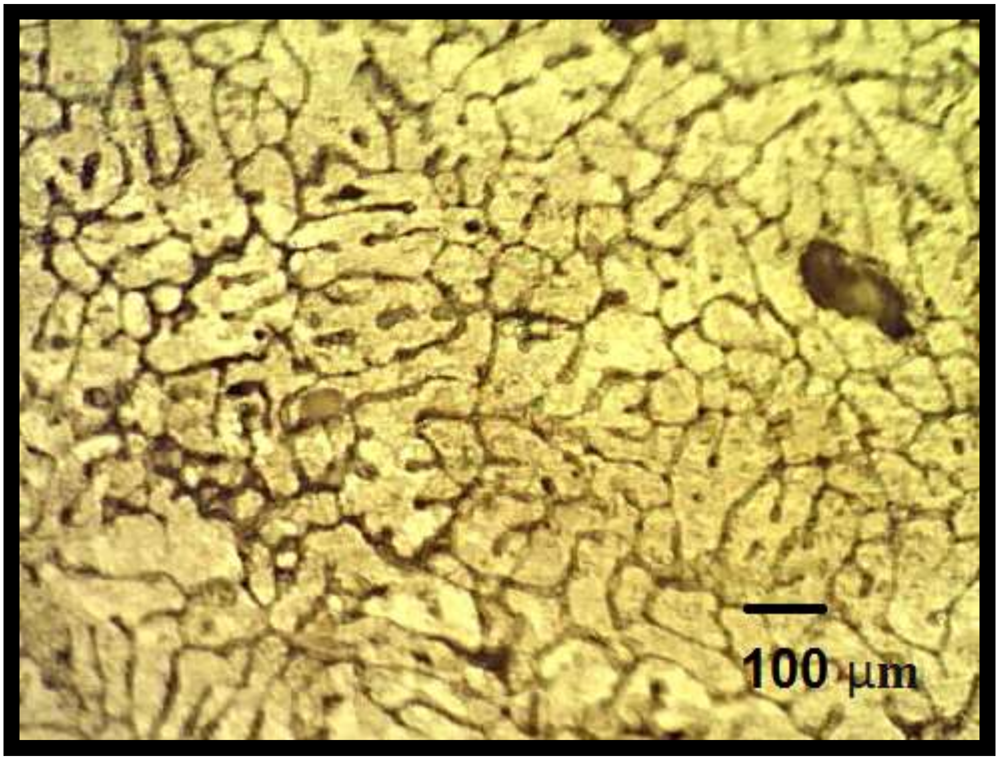



**Figure (11) microstructure of weld zone of TIG joint.**

The weld region of FSW joint contains very fine, equiaxed grains and this may be due to the dynamic recrystallisation that occurred during FSW process [11]. The friction stir weld shown in Figure (12) has a severe flash defect. Under the high pressure of tool-shoulder, the large mass of flash is ejected to the outside. On the other hand, the flash is due to the softening of the metal by the excess tool-shoulder frictional heat input during the FSW.

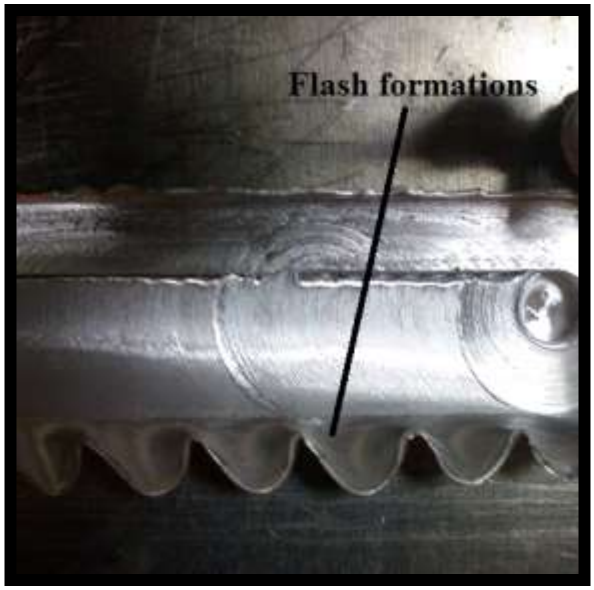



**Figure (12) Flash formations during FSW at 10 mm/min welding speed.**

The microstructure of a tunnel defect at transverse cross-section is given in Figure(13). Around the tunnel defect. Obviously, the formation of tunnel defects is caused by inadequate material stirring or mixing. The material flow direction on the horizontal plane is firstly from the advancing side to the retreating side of friction stir welds [5]. Figure (14) shows the sample of the FSW joint, it contains porousor void Formation on nugget zone and small cracks on the thermo-mechanically affected zone.

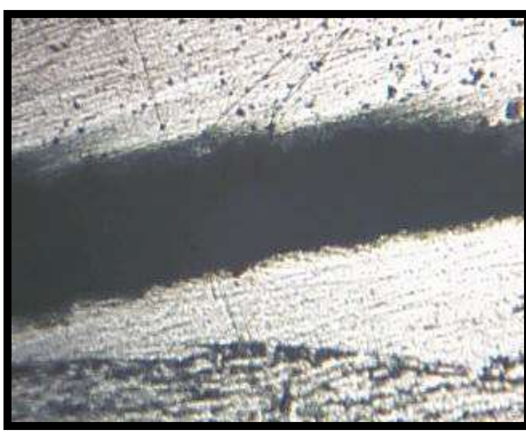


**Figure (13) tunnel defect during FSW at 10 mm/min welding speed.**

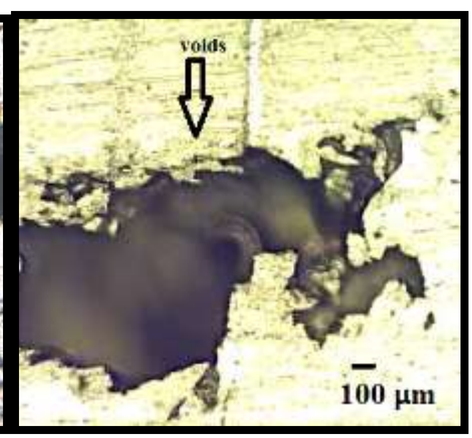



**Figure (14) void Formation during FSW at 1 mm/min welding speed.**

## CONCLUSIONS

The influence of two joining methods, i.e. fusion (TIG) and solid-state (FSW) welding processes, on both microstructure and mechanical properties of AA6061145 aluminum alloy was investigated.

1) The maximum weld strength obtained in this study was (186 Mpa) and (55 %) weld efficiency in the weld using FSW joint.
2) Higher heat intensity in the TIG process negatively affects of the mechanical properties of the welded material. Where Hardness change in the welded material is affected by the amount of the heat input during the welding process.
3) Hardness is lower in the weld center region compared to the HAZ and BM regions irrespective of welding technique. The hardness values are recorded in the TIG joints are lower than that recorded in the FSW joints.
4) The formation of fine, equiaxed grains and uniformly distributed, very fine strengthening precipitates in the weld region are the reasons for higher tensile properties of FSW joints compared to TIG joints.

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