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A Comparison Study of Mechanical Properties between Friction Stir Welding and TIG Welded Joints of Aluminum Alloy (Al 6061-T6)

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ABSTRACT

In this study two different welding processes have been considered, a conventional tungsten inert gas (TIG) and a relatively new solid state welding known as friction stir welding (FSW). TIG welding process has been performed on Al 6061-T6 of thickness 4mm by using filler metal of Al-Mg alloy type (ER5356) according to AWS classification metal with tungsten electrode (EWth-2) and arc voltage of (12V). Various welding currents of (125, 160, 200, 225) Amp were used under argon as shielding gas of flow rate of (15-20 cf / hour) and welding speed of 280 mm/min.

Friction stir welding is carried out using automatic milling machine with five different welding or bed speeds of (25-50-80-100-125 mm/min) and five different tool rotation speeds of (630-800-1000-1250-1600 rpm). Tool steel of type R18 consists of a shoulder with diameter of (20 mm) and pin of diameter (5.5 mm). X-ray radiographic inspection, tensile test and microhardness test of FSW and TIG joints at optimum welding conditions were made.

The results indicate that the best tensile strength of FSW joints is 289 MPa and joint efficiency is 79% which were welded with welding parameters of (1250 rpm, 800 rpm and 50 mm/min, 125 mm/min) respectively. While in case of TIG joint the best tensile strength is 210 MPa and joint efficiency is 57%.

It was found that the microhardness hardness values in the TIG welded joints are lower than that of the FSW joints. The formation of fine equiaxed grains and very fine strengthening precipitates (Mg_2Si) in the stir or weld region are the reasons for higher tensile strength and hardness of FSW joints compared to TIG joints.

Keywords: Friction Stir Welding, TIG, Mechanical Properties, Al-Alloys.

دراسة مقارنة الخواص الميكانكية لوصلات ملحومة بطريقة اللحام بالخلط الاحتكاكي واللحام بقطب التنكستن لسبيكة المنيوم 6061-T6

الخلاصة

في هذه الدراسة تم أجراء عمليتين مختلفتين للحام. عملية اللحام بقطب التنكستن المحمي بالغاز الخامل TIG) التقليدية و لحام الحالة الصلبة الحديث المعروفة باسم اللحام بالخلط الاحتكاكي (FSW). وقد ا نجزت عملية لحام TIG لسبيكة 6061-T6 ذات سمك 4 ملم باستخدام معدن حشو

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من سبيكة الالمنيوم– مغنيسيوم نوع ER5356 طبقا لتصنيف (AWS) مع قطب من التنكستن نوع (EWth-2) وفولتيه لحام 12فولت)وعند تيارات لحام مختلفه 125، 160، 200، 225) امبير بوجود الأركون كغاز حمايه بمعدل تدفق 15-20 لتر ساعة) وسرعة لحام 280 ملم دقيقة.

اما اللحام بالخلط الاحتكاكي فقد نفد باستخدام ماكنة تفريز اوتوماتيكية ذات خمسة سرع لحام مختلفة (سرعة الفرشة) 25-50-80-100-125 مم دقيقة)، وخمسة سرع دوران مختلفه للعدة (630- 800 -1000 – 1250- 1600 دورة في الدقيقة). العدة مصنوعة من الفولاذ نوع R18 يتكون من الكتف بقطر 20 ملم) ومسمار بقطر 5.5ملم).

وقد تم فحص العينات الملحومة بالتصوير الشعاعي بالأشعة السينية ، واختبار الشد واختبار الصلادة الدقيقة للملحومات FSW وTIG في الظروف المثلى للحام.

وتشير النتائج إلى أن مقاومة الشد للملحومات FSW كانت 289 MPa وكفاءة اللحام كانت 79 ٪ للملحومات التي لحمت عند متغيرات لحام 1250 دورة في الدقيقة، 800 دورة في الدقيقة و 50 ملم / دقيقة، 125 ملم دقيقة على التوالي بينما في حالة لحام TIG فان مقاومة الشد كانت 210 MPa وكفاءة اللحام كانت 57٪ .

وقد وجد ان قيم الصلادة في وصلات اللحام TIG كانت اقل مما في وصلات اللحام FSW. ان تكون بلورات ناعمة ومتساوية المحاور وتكون دقائق ناعمة جدا من الطور (Mg_2Si) بالتصليد بالترسيب في منطقة الخلط اواللحام هو السبب في زيادة مقاومة الشد والصلادة باللحام بطريقة FSW مقارنة باللحام بطريقة TIG .

INTRODUCTION

The most significant process for the welding of aluminum to be developed within the last decade of the twentieth century was the friction stir process, an adaptation of the friction welding process. This process was invented at TWI in the UK in 1991 and, unlike the conventional rotary or linear motion processes; it is capable of welding longitudinal seams in flat plate. Despite being such a new process, friction stir welds have already been launched into space in 1999 in the form of seams in the fuel tanks of a Boeing Delta II rocket. Friction stir welding has also been introduced into shipyards with great success and is being actively investigated for applications in the railway rolling stock and automotive industries [1].

Won-Bae Lee et al [2004][2] investigated the microstructure change related with the mechanical properties of a friction stir welded Al 6061 alloy under various welding conditions. Frictional heat and plastic flow during friction stir welding produced fine and equiaxed grains in the stir zone, and elongated grains in the thermo-mechanically affected zone caused by dynamic recovery and recrystallization. Hardness distribution near the weld zone was strongly related to the behavior of precipitates and dislocation density. Especially, hardness of the stir zone at a higher tool rotation speed was higher than that of a lower tool rotation speed due to higher density of spherical shaped precipitates.

A Squillace, et al [2004] [3] investigated microstructure of weld butt joints of AA 2024-T3. 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). Microhardness measurements allow pointing out a general decay of mechanical properties of TIG joints. In FSW joint, instead, lower temperatures involved in process and severe plastic deformations induced by tool motion allow rising of a complex situation: by a general point of view a slight decay of mechanical properties is recorded in nugget zone, flow arm and the rmomechanically altered zone (TMAZ), while in heat-affected zone (HAZ), due to starting heat treatment of alloy under investigation, slight improvement of such properties is appreciated. In flow arm and in nugget zone, however, a slight recovery of hardness, TMAZ zone, is recorded, due to the recrystallisation of a very fine grain structure.

G. R. Babu et al [2008] [4] Investigated the effect of processing parameters on mechanical and microstructural properties of aluminum alloy 6082-T6 friction stir welded (FSW) joints. Different welded specimens were produced by employing variable rotating speeds and welding speeds. Tensile strength of the produced joints was tested at room temperature and the correlation with process parameter was assessed. The experimental results indicate that the process parameters have a significant effect on weld macrostructure and mechanical properties of joints.

M. S. Ali et al [2010] [5] studied the effect of TIG process parameters like current, voltage, electrode diameter, arc travel rate on weldment characteristics , like depth of penetration, depth of HAZ, number of undercuts and area of penetration were examined for the weld beads obtained from experiments. They concluded that with increasing the current supplied during welding at the same speed shows increase in heat flow rate and the depth of penetration increases and reaches a maximum value and then start decreasing, and there is not much change in hardness of the material observed by increasing the rate of heat input.

The aim of the present work is to study a comparison the mechanical properties and the microstructure of welded joints of AA6061-T6 obtained with friction stir welding (FSW) and conventional tungsten inert gas welding (TIG).

EXPERIMENTAL WORK

1-The material used

The material used for welding process was AA6061-T6 aluminum alloy because of its wide applications such a heavy-duty structures requiring good corrosion resistance, truck and marine components, railroad cars, furniture, tank fittings, general structural and high pressure application, wire products, and pipelines[1]. The chemical composition of Al-alloy was analyzed in Specialized Institute for Engineering Industrial /Baghdad as shown in Table (1).

2-Preparation of Plates for Welding

The dimensions of the Al-6061 T6 plates were 100 mm in length, 70 mm in width, and 4 mm thickness. These plates were prepared by using a horizontal milling machine type (Stankoimport, Model 6T13-1-129).

3- Manufacturing of Welding Tool and Fixtures.

3-1 Welding Tool

The friction stir welding experiment has been carried out using tool made from alloy steel type R18, high speed steel, manufactured in (General Foundation for Mechanical Industry/Al- Eskandria) with chemical composition listed in Table (2). Welding tool is designed and machined as shown in Figure(1), then the tool was subjected to heat treatment (hardening and tempering). The tool after heat treatment has average hardness value of 55-56 HRC. The used tool was cylindrical tool with flat pin, the shoulder was concaved and the angle between the edge of shoulder and the pin was 10˚. The shoulder had a diameter 20 mm whereas the pin diameter was 5.5 mm and its height was equal to 3.7 mm which was slightly less than that of material thickness (4 mm). Finally the tool was fitted into a collets and linked to machine spindle which rotated in clockwise direction.

3-2 Fixtures

The fixtures were a backing steel plate (anvil) with a dimensions of (250 mm × 220 mm × 30 mm), that was prepared to be suitable for the milling machine table. The work piece plate to be welded had been fixed using four clamps.

3-3 Welding Procedure

Two prepared pieces of 6061-T6 aluminum alloy were joined in the following steps:

1-Plunging Step

In this step, the spindle was positioned at the centre, and rotates with its certain rpm. The machine table gradually was raised vertically until the tool shoulder plunged with 0.1mm in the plates surfaces, then the spindle rotated with its position for 20 sec (dwelling time) for preheating the plates before welding, this time was measured using stop watch from kislo sports stop watch model K33.

2-Stirring and Welding Step

In this step the stirring and welding process of two plates were conducted, when the machine table moved forward (welding speed) with its certain linear speed (mm/min) to make welding.

3- Retracting of Welding Tool Step

This step started when the central point of the tool reached the given welding length, so the forward movement stopped and the tool was lifted out of the sample leaving hole at the end of the weld which can be cut from the welded joint. The finished joint is seen in Figure(2).

3-4 Welding Parameters

The friction stir welding (FSW) parameters used to join AA6061 plates include rotational speed and welding speed. The rotational speed ranges from 630 to 1600 rpm while the welding speed ranges from 25 to 125 mm/min. The tilt angle is (3^o), plunging depth (0.1 mm) and dwelling time (20 sec) remain constant.

3-5 TIG Welding Process

The dimensions of the plates were 100 mm in length, 70 mm in width, and 4 mm in thickness for butt joint plates prepared by using a horizontal milling machine. Before welding, the plates were preoxidized by stainless steel brush and whipped with acetone solution. The filler metal of Al-Mg alloy type (ER5356) was used in TIG welding according to AWS A5.10-69 classification of chemical requirement for welding rods and electrodes for Al and its alloys [6]. The details of the TIG Welding experiments are summarized in Table(3).

4- Inspection and Tests

4-1 X-Ray Radiography

X-ray radiographic inspection was carried out on the welded plates of FSW joints and TIG joints using radiographic unit operated at 125 kV, 5 mA for duration of 1.5 min to determine the quality of the weldment for pores and discontinuities at weld nugget. Radiographic device used in this work is ICM in General Company of Automobiles, Department of Quality Control.

4-2 Microstructure Examination

The specimens are cut perpendicular to the welding direction, using horizontal milling machine to make sample of dimensions of (4cm × 1.5cm × 0.4cm). Wet grinding step is accomplished by emery paper of SiC with particle size sequentially (320, 500, 800, 1000, 1200) to obtain surface finishes that are ready for polishing. Water is used as a coolant and lubricant to facilitate hand grinding. After that a polishing stage is carried by using special polishing cloth and diamond paste type (nature diamond, with size 0.3 micron) to obtain mirror phished surface. Etching is performed by immersing the prepared specimen in Keller's Reagent (15 ml HF, 45 ml HCl, 15ml HNO_3 and 25 ml H_2O) for (15-20 sec) and washing in water, then in a stream of warm air. Optical microscope (EP-Type2) is used to provide information about the microstructure of welded specimens.

4-3 Hardness Test

Microhardness test was carried out over top side of welded plates using a Zwick & Co. Ko type (Micro Hardness Vickers). The surface being tested generally requires a metallographic finish. It is necessary to determine the hardness over small positions on the surface of base metal, HAZ and weld nugget to indicate the variation in hardness for each place. A load of 400 g was applied and loading time was 20 seconds.

4-4 Tensile Tes*t*

Tensile test is conducted by gripping a specimen at both ends and subjecting it to increase in axial load until it breaks. Recording of load and elongation data during the test allows the investigator to determine several characteristics about the mechanical behavior of the joint. So to perform tensile test the tensile specimens are prepared as follows:

1. Cut 15 mm wide pieces from the welded plates in direction perpendicular to the welding line using horizontal milling machine.
2. Tensile specimens are prepared using vertical milling machine according to the ASTM B 557M-02a sub size specimen geometry. Such that the weld joint is positioned in the middle of the specimen gage length.
3. Remove thin layer from the top and bottom surface using vertical milling machine.
4. Smoothen the tensile specimens using abrasive paper to ensure that no surface scratch is there.

5- Results and Discussion

***5*-1 Microstructure of FSW Welds**

Figure (3) shows the optical micrographs of base alloy 6061-T6 and weld region of FSW joint which was welded with welding parameters of (1250 rpm and 50 mm/min). The base alloy contains elongated grains with uniformly distributed and very fine strengthening precipitates of Mg_2Si. The weld region of FSW joint contains very fine equiaxed grains in stir or nugget zone and this is due to dynamic recrystallisation section that occurred during friction stir welding (FSW) process [7].

In FSW the temperatures are over (200-250) ºC during heating and Mg_2Si (β) is easily dissolved. Grong O. (1997) [8] reports that in HAZ where the temperatures are near or less than 300º C the precipitation of β` is very high and as a consequence, the transition from β to β` by dissolution occurs. In the weld nugget, the temperatures are higher. Therefore Mg_2Si precipitates go into the solution. The nugget hardness recovery is due to recrystallisation of very fine grain structure and by natural aging. In FSW friction heat softens the welded material at a temperature less than the melting point. The softened material under the shoulder is also subjected to extrusion by the rotating tool. The weld material is composed of fewer strengthening precipitates compared to the base metal. In friction stir welding the grain structure can be divided into four zones as shown in Figure 3:

a- Fine equaxied grains in the nugget at the weld center nugget stir zone (NZ).
b- Highly elongated grain with very small cells retreating and advancing side thermo-mechanical affected zone (TMAZ).
c- Slightly elongated coarse grain in the heat-affected zone (HAZ).
d- Base alloy of Al 6061-T6 (BM).

5-2 Microstructure of TIG Welds

Weldments or welds inherently possess compositional and micro structural heterogeneities, which can be classified by dimensional scale. On the largest scale, a weld consists of a transition from wrought base metal through an HAZ and into solidified weld metal and includes five microstructurally distinct regions normally identified as the fusion zone, the unmixed region, the partially melted region, the HAZ, and the unaffected base metal. Not all five zones are present in any given weldment [9].

Figure (4) shows the region of heterogeneities weld of TIG of Al 6061-T6: Fusion zone, Heat-affected zone and base Metal.

The fusion zone: is the result of melting which fuses the base metal and filler metal to produce a zone with a composition that is different from that of the base metal. This compositional difference produces a galvanic couple, which can influence the corrosion process in the vicinity of the weld. This offers microstructure galvanic effect due to segregation resulting from solidification.

The heat-affected zone (HAZ): is the portion of the weld joint which has experienced peak temperatures high enough to produce solid-state microstructure changes but too low to cause any melting. Thus, each position has its own microstructure features and corrosion susceptibility. On a fine scale, microstructure gradients exist within the HAZ due to different time-temperature cycles. Referred to as microsegregation, exists within individual weld beads due to segregation of major and trace elements during solidification [9].

5-3 Hardness Test Results

The hardness over top surface of a friction stir welded joints was measured by Vickers hardness tester. The measured hardness values are presented in Figures (5), **(6), (7).** The as welded FSW joint produced at welding speed of S10 (800 rpm-125 mm/min), S17 (1250 rpm-50 mm/min) has maximum hardness of (86 HV) in weld zone and minimum hardness of (64 HV) in HAZ. Hardness tests were performed through or top surface of welded joints in case of TIG and FSW.

TIG weld joint shows general reduction in hardness in weld metal and HAZ and with an increase towards base alloy. This is due to phase transformed induced by fusion weld metal and high temperatures in experiment by material. While FSW weld joints show similar distribution of hardness over four zones. FSW joint shows great difference among four different zones: nugget zone or stir zone (SZ), thermo-mechanical affected zone (TMAZ), heated affected zone (HAZ) and base metal (i.e. parent alloy).The SN and HAZ zones are characterized by general drop of hardness even through the nugget and flow arm zone show a high microstructure recovery due to very fine grain structure while the (TMAZ) shows a slight increase in the hardness. It can be seen that HAZ shows noticeable drop in hardness unit reaching the base alloy (Al-6061) which shows the highest hardness (109.5 HV). The hardness at weld center of as FSW welded joints is higher (varies between 82-86 HV) than the HAZ because the hardness in nugget zone recovers slightly due to recrystallization to very fine equaxied grain structure.

Liu, et al [10] reports that averaging and dissolving of the metastable precipitates lead to the decrease in the micro hardness in the weld zone of friction stir welding of Al 6061-T6 and generate a region of relatively low hardness value around weld center. This zone extends up to the transition of TMAZ and HAZ. This is due to coarsening/ dissolution of strengthening precipitates (Mg_2Si). Maximum hardness occurs in TMAZ because aging strengthens the welds [11]. Hardness a gain increases toward the base metal. Because there is a difference in plastic deformation between advancing and retreating sides, a significant difference is produced in precipitate microstructure, as well as the difference in thermal cycles on both sides, unsymmetrical micro hardness profile can be pointed out. The micro-hardness values in welding center of FSW joint at welding speed of 50mm/min show in Table (4).

5-4 Tensile Strength Test Results:

Table (5) shows the results of tensile strength of base alloy 6061-T6 and TIG welds (which were welded at welding current of 200 Amp) and friction stir welds at optimum welding conditions or parameter of S10 (800 rpm-125 mm/min), S17 (1250 rpm-50 mm/min). The tensile strength of TIG weld was lower than that of FSW welds, the maximum joint efficiency was obtained by using the following rotation for FSW produced at optimum welding conditions it was (79%).

Joint Efficiency = Ultimate tensile strength of weld /ultimate tensile strength of base metal x 100.[12]

It was seen that with increasing welding speed or tool rotations speed the tensile strength and joint efficiency were increased. **Cavalier, et al** [13] also reported similar results for the tensile strength which increases with increasing welding speed (80-115 mm/min). This is due to reduced dissolution of precipitates owing to less heat generation per unit length during FSW, while TIG weld results in coarsening of second phase particles and grain during fusion welding.

A decrease in tensile strength was observed and joint efficiency for FSW welds was produced at low welding speed/and tool rotation speed. Because the friction stir welding process softens the material significantly which in turn decreases the tensile strength and increases the ductility of the material, this may be attributed to the reduction in dislocation density and elimination of strengthening precipitates [14].

Figures (8 ,9 ,10 and 11) show tensile stress - strain curves of base alloy 6061-T6 and friction stir welds at optimum welding conditions or parameter of S10 (800 rpm-125 mm/min), S17 (1250 rpm-50 mm/min) and TIG welds (which were welded at welding current of 200 Amp).

CONCLUSIONS

1. The optimum welding conditions in FSW joints are (1250 rpm-50 mm/min) and (800 rpm-125 mm/min) which give maximum tensile strength and joint efficiency of (79%) of base alloy compared to that of TIG joint of (57%).

2. The formation of fine, equiaxed grains and uniformly distributed very fine strengthening precipitates in the weld region is the reason for higher tensile properties of FSW joints compared to TIG joints.
3. FSW of Al alloy results in fine recrystallized grains in weld nugget which has been attributed to frictional heating and plastic flow.
4. The microstructure examination shows four welding zones in FSW joint while three zones in TIG joint of Al 6061-T6.
5. Micro hardness tests confirm the general decay of mechanical properties induced by higher temperature experienced by material in case of TIG joint.
6. Micro hardness tests performed in case of FSW joint show great differences among four different zones: nugget zone, TMAZ, HAZ (Heat affected zone) and base metal.
7. The hardness of FSW weld is higher than that of TIG. While the base alloy Al 6061-T6 exhibits higher hardness when compared with welded joints (TIG, FSW).

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Table (1) Standard and measured chemical composition (wt%) analysis of Al 6061-T6.

Elements wt%	Standard Value	Measured Value
Mg	0.8 - 1.2	0.958
Si	0.40 - 0.8	0.588
Cu	0.15 -0.40	0.251
Cr	0.04 -0.35	0.175
Fe	≤ 0.7	0.454
Zn	≤ 0.25	0.042
Ti	≤ 0.15	0.03
Mn	≤ 0.15	0.068
Total Other	≤ 0.15	-
Al	Remainder	97.4

Table (2) Chemical composition (wt%) of the R18 tool steel.

C	Si	Mn	Ni	S	P	Cr	Mo	W	V	Co	Cu	Fe
0.73 - 0.83	0.2 - 0.5	0.2 - 0.5	max 0.6	max 0.03	max 0.03	3.8 - 4.4	max 1	17 - 18.5	1 - 1.4	max 0.5	max 0.25	Rem

Table (3) TIG Welding parameters used in this study.

Weld characteristic	Weld detail
Weld Type	Square Butt Joint
Material Thickness	4 mm
Length of the Weld	100 mm
Welding Direction	Parallel to the cold work direction
Filler Metal	ER5356 (AWS A5.10-69)
Filler Rod Diameter	3.25 mm
Tungsten Diameter	4 mm
Shielding Gas	Argon
Tungsten Type	EWTh-2
Gas Flow Rate	15-20 (cf / h)
Welding Speed	280 mm ⁄ min
Arc Voltage	12V
Welding current	200 Amp

Table (4) The microhardness hardness values in welding zones of welded joints (FSW, TIG).

Specimen Number	Tool Rotation Speed (RPM)	Welding Speed (mm/min)	HV_{500} Number in nugget zone
S2	630	50	74.4
S7	800	50	84
S12	1000	50	84.7
S17	1250	50	86
S22	1600	50	79.5
S28	200 A	/	64

Table (5) shows the results of tensile strength of welded joints (FSW), (TIG) at optimum welding conditions.

Specimen Number	Tool Rotation Speed (RPM)	Welding Speed(mm/min)	Tensile strength (MPa)	Joint efficiency %
S4	630	100	263.2	72
S10	800	125	289.5	79
S13	1000	80	289.5	79
S17	1250	50	289.5	79
S22	1600	50	236.8	64
S 28	200 A current	280	210.5	57
S30	Base alloy 6061-T6	/	368.4	/

Figure (1) Welding Tool used in this study.

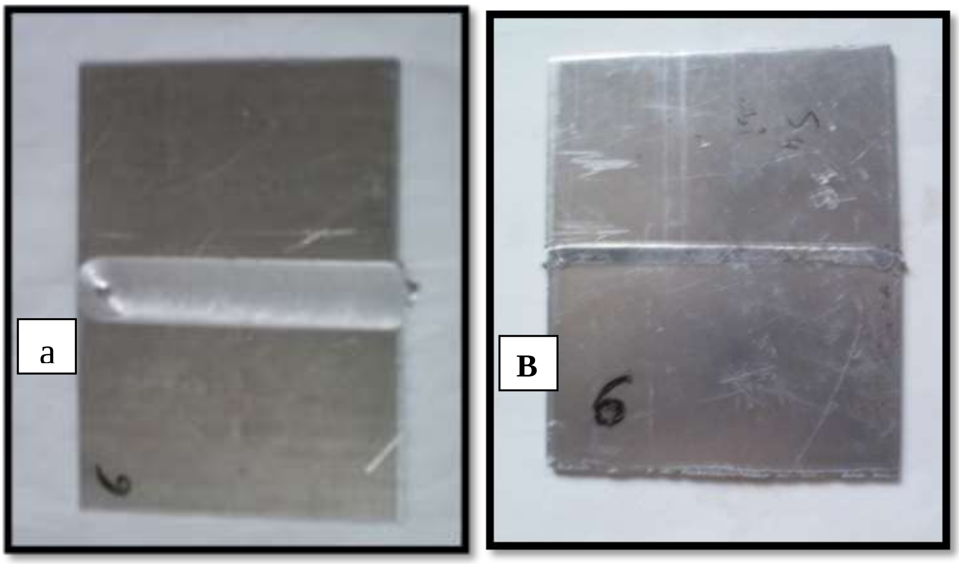

Figure (2) Configurations FSW welded plates a- The top side of butt welded plates b- The back side of butt welded plates.

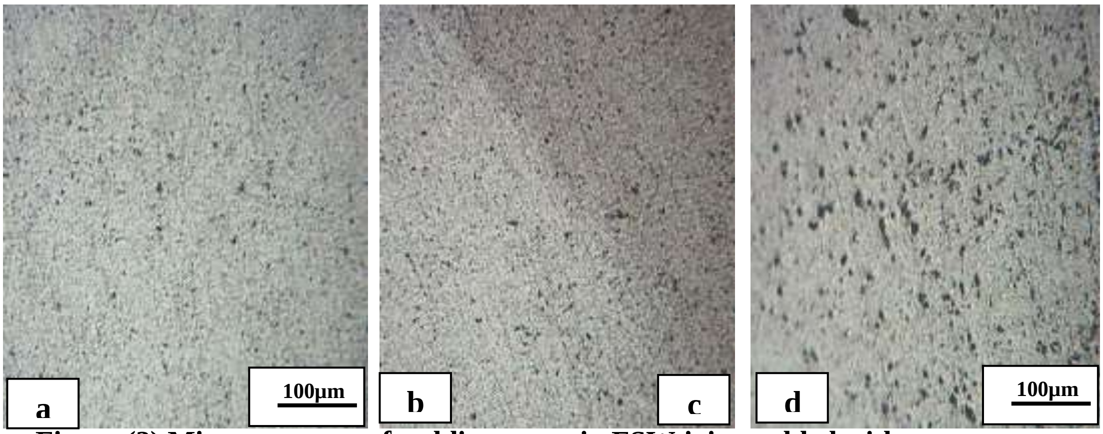

Figure (3) Microstructure of welding zones in FSW joint welded with welding parameters of (1250 rpm and 50 mm/min).
a) Stir zone b) TMAZ C) HAZ d) base alloy.

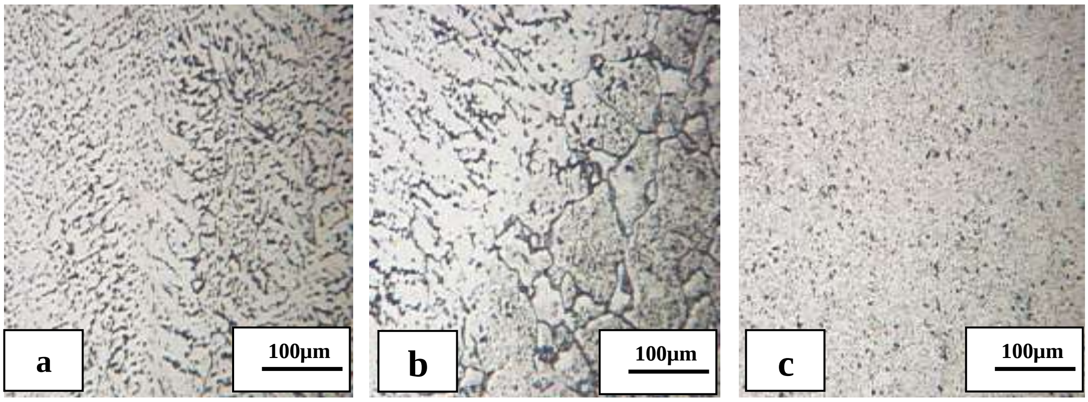

Figure (4) The microstructure of welding zones in TIG joint welded with welding current of 200 Amp , arc voltage of 12 V and welding speed of 280 mm/min:a) Weld metal b) HAZ c) base alloy.

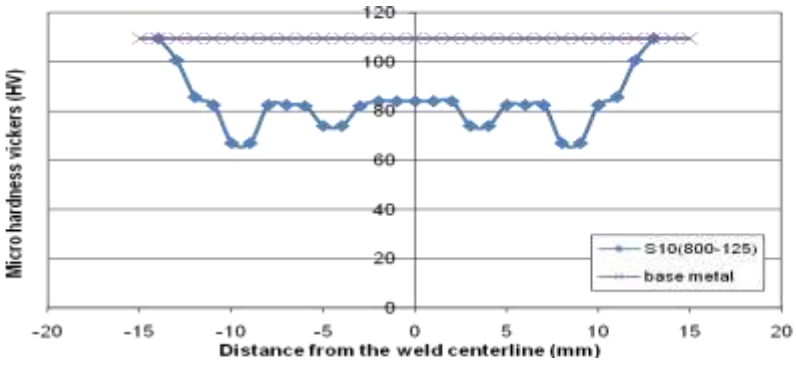

Figure (5) Microhardness profile in FSW joint welded at S10 (800 rpm-125 mm/min).

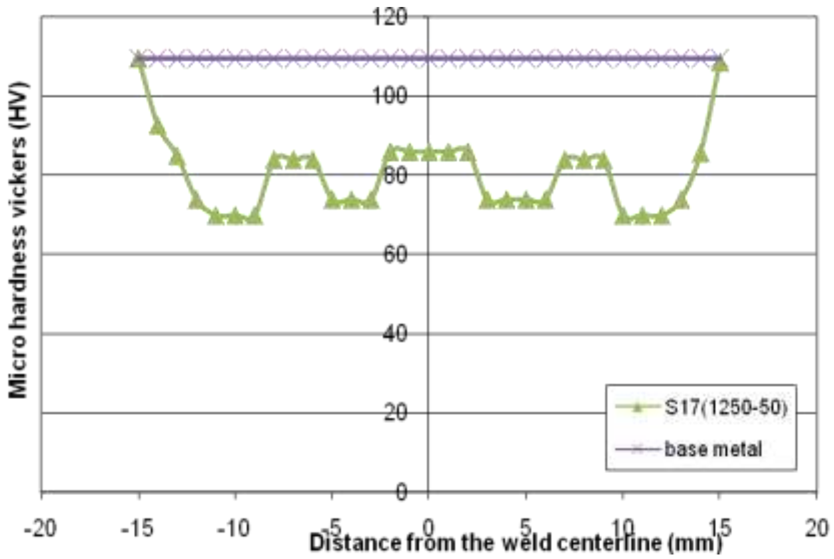

Figure (6) Microhardness profile in FSW joint welded at S17 (1250rpm-50mm/min).

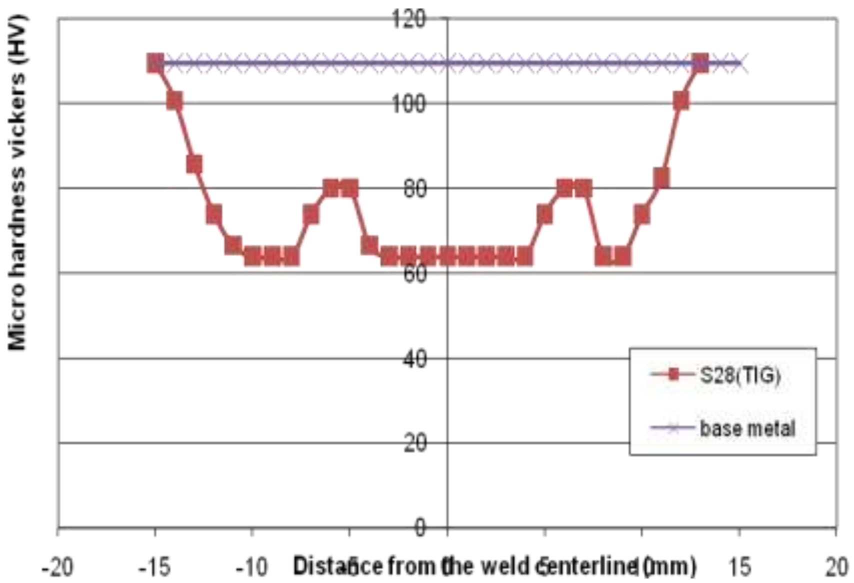

Figure (7) Microhardness profile in TIG joint (sample S28) welded at welding current (200Amp).

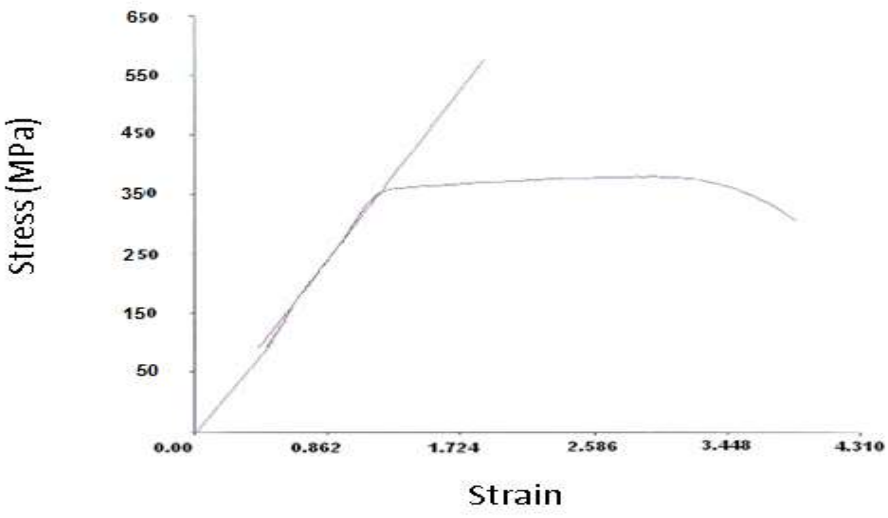

Figure (8) Stress-Strain curve for base alloy (AA 6061-T6).

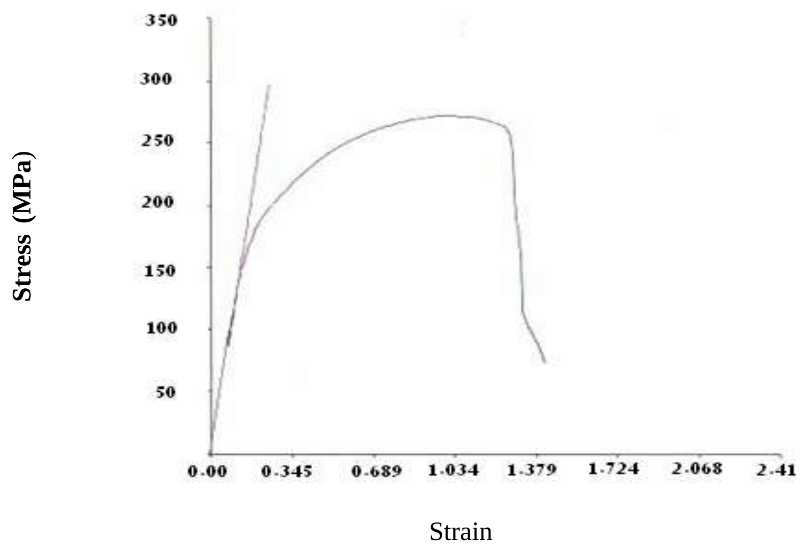

Figure (9): Stress-Strain curve for FSW joint welded at (800 rpm 125mm/min).

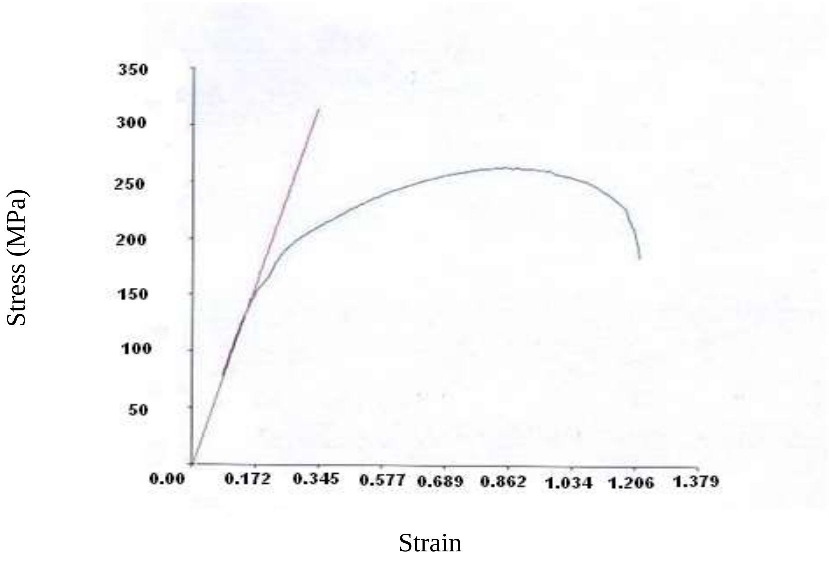

Figure (10) Stress-Strain curve for FSW joint welded at (1250 rpm50mm/min).

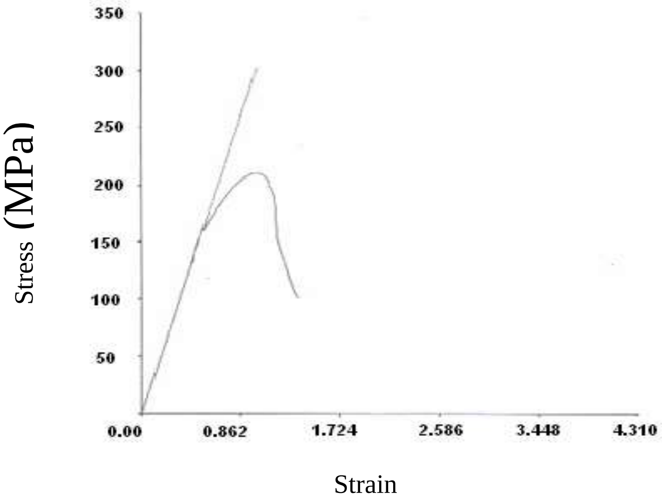

Figure (11) Stress-Strain curve for TIG joint welded at welding current 200 A.