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Corrosion Resistance of Synergistic Welding Process of Aluminium Alloy 6061 T6 in Sea Water

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Abstract

This work involves studying corrosion resistance of AA 6061T6 butt welded joints using Two different welding processes, tungsten inert gas (TIG) and a solid state welding process known as friction stir welding, TIG welding process carried out by using Rolled sheet of thickness6mm to obtain a weld joint with dimension of (100, 50, 5) mm using ER4043 DE (Al Si_5) as filler metal and argon as shielding gas, while Friction stir welding process carried out using CNC milling machine with a tool of rotational speed 1000 rpm and welding speed of 50mm/min to obtain the same butt joint dimensions. Also one of weld joint in the same dimensions subjected to synergistic weld process TIG and FSW weld process at the same previous weld conditions.

All welded joints were tested by X-ray radiography and Faulty pieces were excluded. The joints without defects used to prepare many specimens for Corrosion test by the dimensions of (15*15*3) mm according to ASTM G71-31. Specimens subjected to micro hardness and microstructure test.

Corrosion test was achieved by potential at scan rate(+1000 ,-1000mv/sec) to estimate corrosion parameters by extrapolator Tafle method after polarized ±100 mv around open circuit potential,in seawater (3.5%NaCl) at a temperature of 25°C.

From result which obtained by Tafel equation. It was found that corrosion rate for TIG weld joint was higher than the others but synergistic weld process contributed in improving TIG corrosion resistance by a percentage of 14.3%. and FSW give the lest corrosion rate comparing with base metal.

Keywords: *corrosion resistance, TIG welding, FSW welding aluminum alloy, sea water.*

1. Introduction

Gas metal arc welding is a process that melts and joins metals by heating them with an arc established between a continuously fed filler wire electrode and the metals. Shielding of the arc and the molten weld pool is often obtained using inert gases such as argon and helium. This is the most widely used arc welding process for aluminum alloy. With TIG welding using alternating current (AC) polarity and high heat generation end is continuously changing. An electric arc is formed between inconsumable tungsten Electrode and the work piece. The arc provides the thermal energy to melt the work piece as well as the filler material. For Al alloy due to their elevated thermal conductivity, the weld penetration remains very shallow [1] [2]

The welding of aluminum and its alloys has always represented a great challenge for designers and technologists. As a matter of fact, lots of difficulties are associated to this kind of joint process, mainly related to the presence of a tenacious oxide layer, high thermal conductivity, high coefficient of thermal expansion, solidification shrinkage and, above all, high solubility of hydrogen, and other gases, in molten state Further problems can arise when attention is focused on heat-treatable alloys, since heat, provided by welding process, is responsible of the decay of mechanical properties, due to phase transformations and softening induced in alloy.

As a consequence of all above-mentioned problems, additional problems arise when corrosion resistance characteristics become relevant in this case phase transformations induced in alloy structure often result into a deep modification of materials properties [3].

These problems can be eliminated by Friction stir welding (FSW) process. Friction Stir Welding (FSW) is a solid state joining technique using a tool with a probe attached to its tip rotated while being pushed against the butt sections of the pieces of metal to be welded. The frictional heat generated by this process softens the metal to produce a plastic flow that effectively stirs the metal from the sections on both sides and melting them together to create a weld.

FSW is depend on the welding parameters such as pin rotation speed, traverse speed and stirrer geometry. In order to increase the welding efficiency mechanical properties of joints must be maximized and the defects must be minimized in the friction stir welding (FSW) process [1] [2]

Aluminum is actually a very active metal and it instantly reacts with oxygen to form aluminum oxide . This aluminum oxide layer is chemically bond to the surface , and it seals the core of aluminum from any further reaction. This oxide film gives aluminum excellent corrosion resistance in a wide range of water and soil conditions this oxide layer can become unstable exposed to extreme PH levels when the environment is highly or basic acidic . Protective oxide film is generally stable in the pH range of (4.5 to 8.5) , the pH of seawater remains within the domain of stability of the natural oxide film. This explains the good corrosion resistance of aluminum in seawater [4] This resistance associated with its composition, structure, defect , surface condition and the various types of environments in seawater we can see that many variable parameters effecting the corrosion resistance like speed of media and temperature [5] [6]

Many studies have investigated the corrosion resistance of aluminum weld joint alloy in seawater.

Yadong Zhao [7] made comparative between electrochemical corrosion behavior of friction stir welded 6061 aluminum alloy and 6061 parent material by static weight loss experiment (gravimetric test), using potentiodynamic polarization curve and scanning electron microscopy (SEM), from results he found that The corrosion rate of the weld with the tool rotation rate of 800 r/min and the traverse speed of 160 mm/min, was less than that of the parent material; and the weld showed more positive corrosion potential, and less current density, larger Rp (polarization resistance) than the parent material and by using SEM observation showed that a few shallow pits were presented on the surface of the weld. However, a large number of deeper pits emerged on the surface of the parent material.

Ratnesh K. Shukla [8] studied microstructure, micro hardness distribution and tensile properties of weld butt joints of 6061 T6 aluminum alloy using two welding processes, friction stir welding and tungsten inert gas welding. Results showed a general decay of mechanical properties of TIG joints, mainly due to high temperature experienced by the material. Instead, in FSW joint, lower temperatures are involved in the process due- to severe plastic deformation induced by the tool motion and lower decay of mechanical properties. In the nugget zone a slight recovery of hardness is observed due to recrystallization of very fine grain structure

V.Fahimpour [9] studied the. Corrosion behavior of the welding zone of (FSW) and gas tungsten arc welding (GTAW) methods for AA6061 using Tafel polarization curve, deducting that resistance to corrosion was greater for the FSW grains than the GTAW structure. In both cases, susceptibility to corrosion attack was greater in the welded region than the base metal section.

Prince Saini [10]studied the feasibility to weld of two pieces of aluminum alloy (AA 6061) sheets of thickness 6mm by friction stir welding process and study its effect on hardness of the welding joints with respect to welding speed. Special welding fixture fixed on conventional milling machine has been conducted to attempt this welding with three tool rotation speed 1950,3080,4600 (r.p.m) with feed rate.20,25,30 (mm/sec). Mechanical property (Hardness Number) was investigated using Hardness testing machine. Based on the stir welding experiments conducted in this study results show that aluminum sheet (AA 6061-T6) can be welded by (FSW) processes with maximum welding efficiency in terms of hardness number, using rotational speed 3080 (r.p.m), and Feed rate 30 (mm/sec).

The aim of this study is to apply a synergistic welding method to improve corrosion resistance of AA 6061 T6 and compare the results with other welding processes.

2. Experimental Work

2.1. Metal Selected

The base metal used in this work was of AL alloy 6061-T6, which its chemical composition provided in Table (1) by using ARL Spectrometer.

2.2. welding Joint

Six Rolled sheet of 6 mm thickness were machined to the required dimensions (100 mm * 50mm *5).for TIG welding Butt joints using argon as shielding gas and ER4030 ($AlSi_{5}$) as filler material with a chemical composition shown in Table (2), the other parameters were: welding current 70 amperes, voltage 25 volts, filler rod diameter 3 mm, welding speed 120 mm/min, gas flow 20 lit/min. Figure (1).

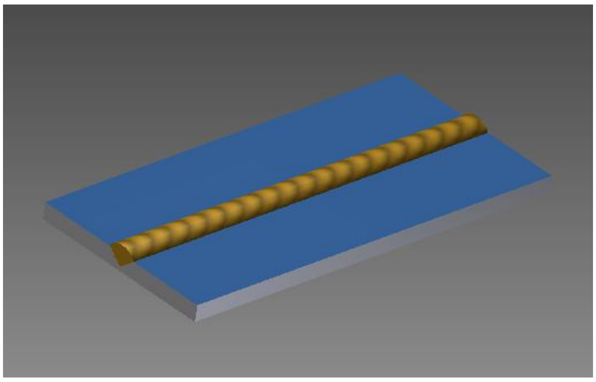


Fig. 1. TIG weld joint.

Friction stir welded joint performed by attaching two plates together using CNC milling machine with motor of 11 KW , rotating tool assembly at 1000 rpm rotational speed and welding speed of 50 mm/min. The material for the tool was tool steel which was hardened to58 HRC. The tool used had shoulder diameter of 14 mm, top pin diameter of 5.5 mm, bottom pin diameter of 3 mm and pin height 3.85 mm . The pin was left hand threaded and tool was rotated in counter clock wise direction

Another butt weld joint processed in the same dimensions by subjecting to synergistic weld process first TIG then FSW weld process.

All welded pieces were tested by X-ray radiography and faulty pieces were excluded, and the joints without defects used to prepare (12) specimens for corrosion test by the dimensions of (15*15*3) mm according to ASTM (G71-31) include three specimens from each weld joint and to get perfect dimensions of the specimens and to avoid mistakes, an accurate dimensions should be attained. All specimens were machined using programmable CNC machine. During manufacturing of the specimens, careful control was taken into consideration to produce a good surface finish.

Table 1,
Chemical composition of the used metal 6061- T6 .

Elements Wt%	Measures value	Standard value[12]
Si	0.6	0.4-0.8
Fe	0.4	Max 0.7
Cu	0.3	0.15-0.4
Mn	0.12	Max 0.15
Mg	1.0	0.8-1.2
Cr	0.2	0.04-0.35
Zn	0.18	Max 0.25
Al	Rem	Rem

Table 2,
Chemical composition of the filler metal (Filer wire ER 4043) Al Si_{5}.

Elements Wt%	Actual value	Nominal value[12]
Si	5.0	4.5-6
Fe	0.4	<0.6
Cu	0.1	<0.3
Mn	0.08	<0.3
Mg	0.06	< 0.2
Cr	0.25	-
Zn	0.15	< 0.1
Sn	0.15	-
Al	93.44	Rem

2.3. Categorization of Weld Joint

After completing the specimen, they were categorized to groups as shown in Table (3).

Table 3,
Categorization of Specimens.

Specimen Symbol	State
A	Native metal
B	FSW weld joint
C	TIG weld joint
D	TIG+ FSW weld joint

2.4. Microstructure Examination

Optical microscopy was used to observe the welded joints and base metal microstructure. The specimens are treated with Sic emery paper of grades 120,350,500,800.Then polished with cloth and alumina Al_2O_3 solution. Etched by Keller's reagent consisting of 95 ml distill water, 2.5 ml HN O3, 1.5 ml HCl and 1 ml HF. Photographs of the Micro structure are shown in Figure 2.

2.5. Micro Hardness Test

The Vickers hardness profile of the weld zone was measured on a cross section perpendicular to the welding direction using micro hardness tester with 200 gms load for 15 sec. Three specimens are used to perform the Vickers hardness test. The average value of three readings is recorded Figure 3.

2.6. Corrosion Tests

The corrosion solution was 3.5 wt %NaCl which was by dissolve in 35 gm of sodium chloride (NaCl) in1000ml of distilled water. The pH was measured by pH meter and was found to be 6.9.

Polarization resistance tests were used to obtain the corrosion rates. Cell current readings were taken during a short, slow sweep of the potential. The sweep was taken from (-100 to + 100) mV relative to (OCP). Scan rate defines the speed of the potential sweep in mV/sec. In this range the current density versus voltage curve is almost nearly linear. A linear data fitting of the standard model gives an estimate of the polarization resistance, which is used to calculate the corrosion current density (Icorr) and corrosion rate. The tests were performed by using a WENKING Mlab multi channels potentiostat and SCI-Mlab corrosion measuring system from Bank Electroniks-Intelligent control GmbH, Germany 2007, as shown in Figure 2. In this test, aluminum alloy (6061-T6) weldment samples were used as working electrode (anode electrod) ,a saturated calomel electrode immersed in the salt solution was used as reference electrode (RE), and a platinum electrode was used as auxiliary electrode (AE) three specimens which repared as above are used to perform the corrosion test. The values of three readings are recorded and it was show fitting in result which obtained.

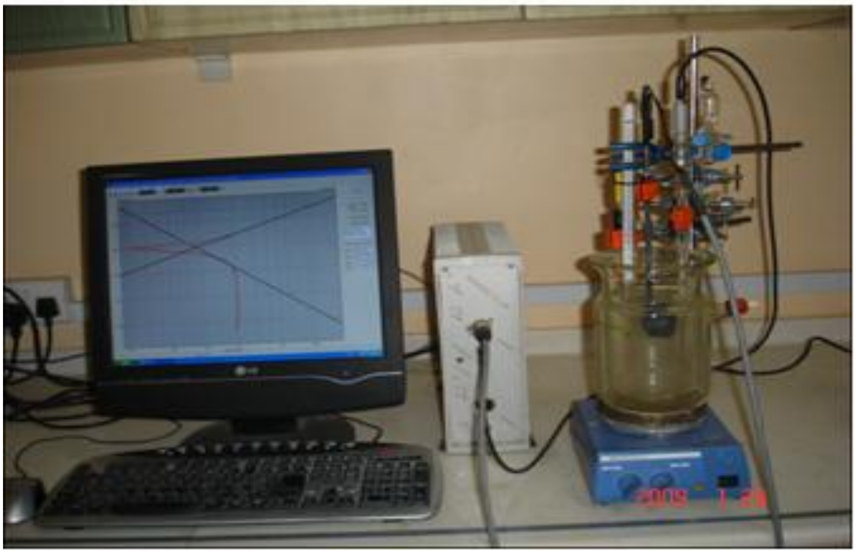


Fig. 2. The electrochemical corrosion unit.

3. Results and Discussion

The variation in microstructures across the welded joint and base metal are shown in Figures (3). Microstructural analysis revealed a coarse, elongated grain structure in the 6061-T6 base metal Figure 3 (A) due to presence of alloying elements such as silicon and magnesium. These two elements combine and undergo precipitation reaction and form strengthening precipitates Mg_2Si as shown by darken particles and fine grain boundary precipitates are evident.

During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and equiaxed recrystallized grains Figure 3(B) The dynamic recrystallization grains caused to the density of dislocation of the sample decreased. At the same time, after severe plastic deformation (SPD), the change of actual microstructure of FSW sample made the weld chemically homogenized. In the weld nugget,the temperatures are higher. Therefore Mg_2Si precipitates go into the solution. The nugget hardness recovery is due to recrystallization 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.

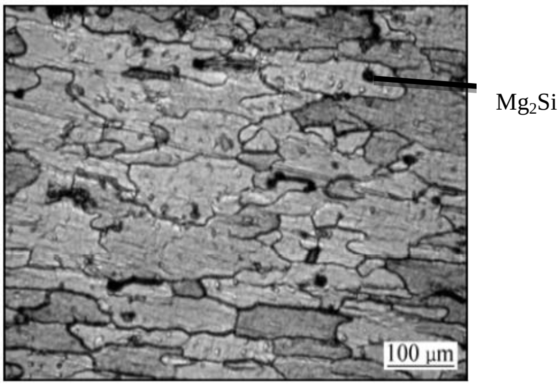
The fusion zone of TIG welded joints contain dendritic structure: is the result of melting which fuses the base metal and filler metal to produce a zone with a composition that is different from that of the base metal. This compositional difference produces a galvanic couple, which can influence the corrosion process in the vicinity of the weld. This offers microstructure galvanic effect due to segregation resulting from solidification and this may be due to fasting welding heating of the base metal and fast cooling of molten metal. specimens(C) in Figure 3 On the largest scale, consists of a weld a transition from wrought base metal through an HAZ and into solidified weld metal and includes five micro structurally 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 element [12].

Microstructure in sample Fig.3 D subjected to a TIG weld processes which gives a dentrtic microstructure then it is subjected to an intense plastic deformation caused by FSW processes resulting a recrystallization of fine grain in structure.

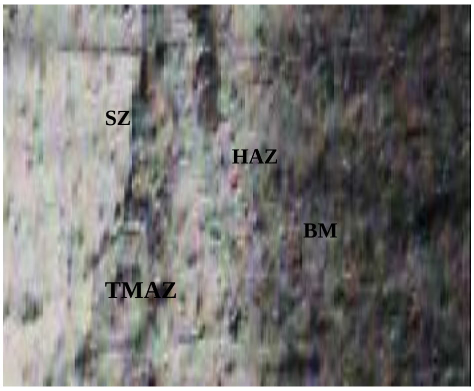
The variations in the hardness measured across the welded specimen from the weld center towards the base metal are shown in Figure (3). In FSW processes the averaging and dissolving of the metastable precipitates lead to the decrease in the micro hardness in the weld zone of friction stir welding of Al 6061-T6 (68Hv) and generate a region of relatively low hardness value (72 Hv)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 [10,].Hardness a gain increases toward the base metal (120Hv). 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. TIG weld joint shows that the hardness in base metal was 120 Hv. while in the weld metal region was 55 Hv. This shows that the hardness is reduced in TIG joint due to higher heat input and use of lower hardness ER4030 ($AlSi_{5)}$ filler metal.

Table 4,
Corrosion Result for all Specimens.

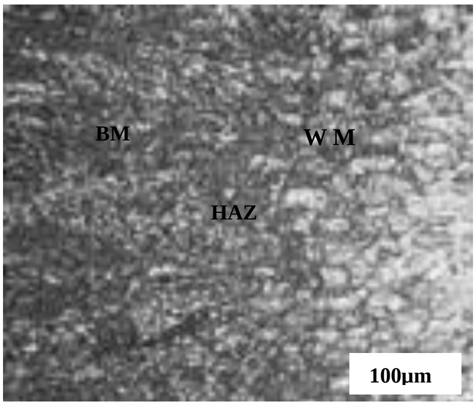
Specimen symbol	I corr. μAmp	Ecorr mV	Corrosion rate mpy
A	10.31	-858.3	4.433
B	3.94	-713.2	1.694
C	34.23	-732.9	15.007
D	29.9	-653.9	12.85



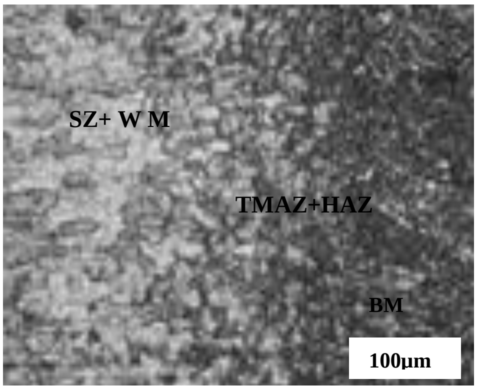
Specimen (A)



Specimen (B)



Specimen (C)



Speceimen (D)

Fig. 3. The microstructure for all specimens.

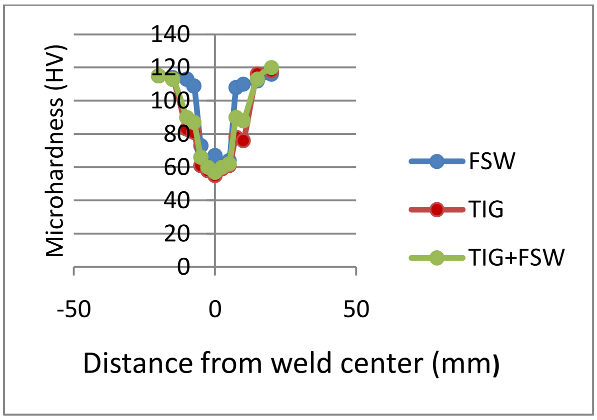


Fig. 4. Micro hardness distribution for the welded joints.

Electrochemical corrosion test by Tafel extrapolation method was carried out on all samples of base alloy of 6061-T6 and weld joint in sodium chloride solution of 3.5% NaCl to determine corrosion Parameters, such as corrosion potential (Ecorr) and corrosion current (Icorr). These parameters will leads to calculate the corrosion rate according to the equation below [13].

$$C.R\ (m.p.y) = 0.13 * I_{corr} * eq.wt / \rho \qquad ...(1)$$

Where

m.p.y mille-inches per year.

I_{corr} corrosion current density (µA/cm^2).

E.W equivalent weight of the corroding species.

P density of the corroding species, (g/cm^3).

Fig. (5) shows the polarization curves of the all specimens which categorized in Table (2), These curves show the cathodic and anodic regions.

Based on E_{cor}, I_{cor} results obtained from polarization measurements in Table 4 and observed in Figure (5).corrosion potential depends on the electrochemical behaviour of the microstructure and this is directly dependent on the quantity of the present phases. Course intermetallic particles that are enriched from magnesium and silicon would lead to dilution of matrix from these alloying elements Therefore, dilution of matrix from magnesium and silicon tends to be the main reason for anodic behaviour of the BM specimen (Sample A). According to fine precipitates of magnesium silicide (Mg_2Si) would form and dispersed throughout the matrix [9]

The corrosion rate of FSW sample (B) weld of the tool rotation rate of 1000 (r.p.m), was less than that of 6061 parent material sample (A). The corrosion potential of the weld was more positive than that of 6061 parent material, while the corrosion current density was less than that of 6061 parent material. This is because WM area behaves as cathode and the BM is an anode.

These fine precipitates are slightly more anodic than the aluminium matrix. Thus, corrosion potential of the remainder matrix would increase due to dilution of matrix from these elements. Based on Table4, it is confirmed that there is an increase of corrosion potential [14] for Sample C. The BM showed higher corrosion rate than the WM in all conditions. The higher corrosion rate in BM is contributed to the presence of secondary phases in the microstructure.

These particles are different than the matrix, thus, a potential difference occurs between them. Intermetallic particles are found to be favourable sites for cathodic reaction as compared to Al matrix [9]

All welding specimen gives lower corrosion compared with base metal because of the metallurgical changing in microstructure during welding. Figure (6) shows the corrosion amount for each specimens as discussed above.

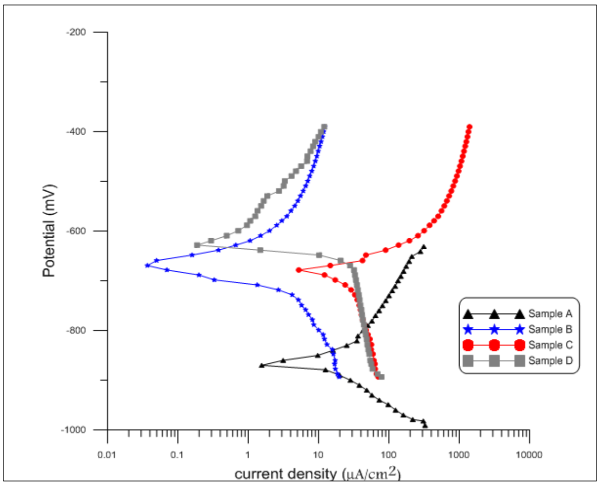
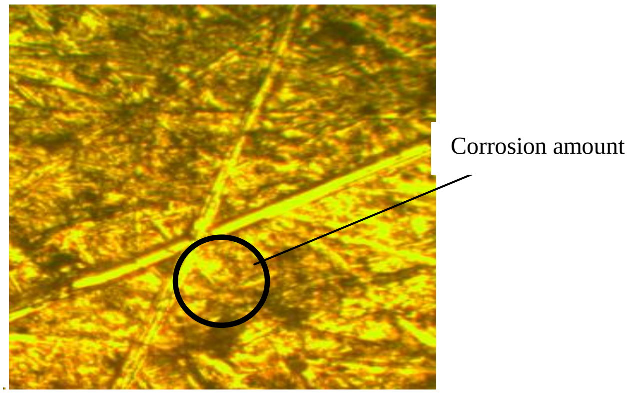
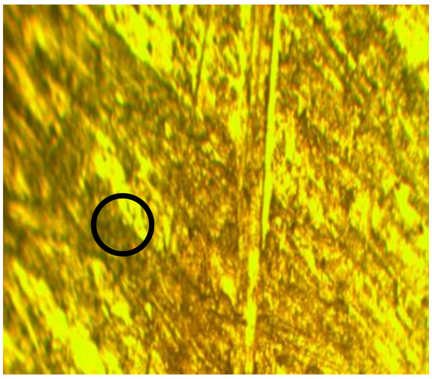


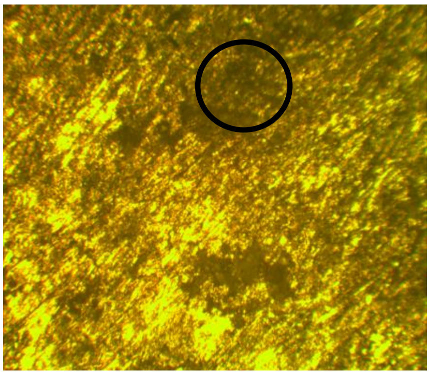
Fig. 5. the electrochemical behavior polarization for all specimens.



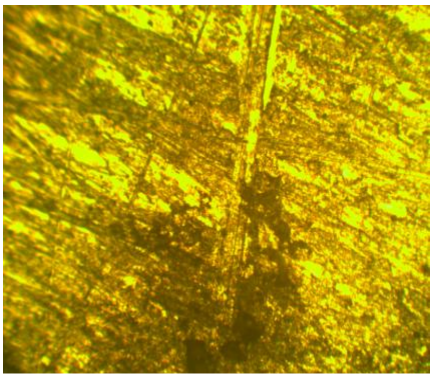
Specimen (A)



Specimen (B)



Specimen (C)



Specimen (D)

Fig. 6. Corrosion photos at 400 x.

4. Conclusions

1. The microstructure of the FSW weld consisted of very fine grains in comparison of the grains of parent material.
2. The corrosion rate of FSW weld joint which obtained using tool rotation rate of 1000 r/min, the traverse speed of 50 mm/min, was less than that of 6061 parent material.
3. The corrosion potential of the weld was more positive than that of 6061 parent material, while the corrosion current density was less than that of 6061 parent material.
4. TIG weld process gives the highest corrosion rate comparing with the other welding processes due to the change in microstructure.
5. Corrosion in TIG specimen improved by using a FSW processes over the TIG weld processed with a percentage of 14.3%,

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مقاومة التاكل لوصلات لحام بطرق مختلفة لسبيكة المنيوم 6061-T6 في ماء البحر

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الخلاصة

تضمن البحث دراسة مقاومة التآكل لوصلات لحام تناكبية لسبيكة المنيوم 6061-T6 تم لحامهم بطريقتي لحام هما لحام القوس الكهربائي باستخدام قطب التنكستن بوجود غاز خامل وطريقة لحام الخلط الاحتكاكي اذ تم لحام وصلتين بابعاد ١٠٠,٥٠,٥ ملم بسلك لحام نوع(ER4043 ED(AL Si_5 وسرعة لحام 120mm/min مع وجود غازخامل هو االاركون وبسرعة تدفق 20 L/min على صفائح من السبيكة المستخدمة .

وان لحام الخلط الاحتكاكي للحصول على وصلة لحام بالابعاد السابقة نفسها نفذ باستخدام ماكنة مبرمجة وبقلم لحام دائري يدوربسرعة هي 1000 دورة بالدقيقة و سرعة لحام 50 ملم/ دقيقة

وقد تم تطبيق لحام الخلط الاحتكاكي على وصلة ملحومة بطريقة القوس الكهربائي باستخدام قطب التنكستن للحصول على وصلة لحام ثالثة بالابعاد نفسها وبنفس ظروف اللحام للطريقتين

بعد عملية اللحام والتاكد من خلو الوصلات من العيوب من خلال فحصها بواسطة جهاز radiography X-ray تم تحضير عينات اختبار التاكل بعد قطعها من الوصلة بابعاد ١٥*١٥*٣ ملم على وفق المواصفة القياسية ASTM G71-31 اتبعتها عمليات تحضير من تنعيم وصقل لاجراء فحص البنية المجهرية باستخدام المجهر الضوئي ذي كاميرا للتعرف على البنية المجهرية ثم اجراء فحص الصلادة المايكروية.

اجري اختبار تاكل كهروكيمياوي بطريقة المجهاد الساكن اذ تم امرار تيار كهربائي في خلية تتألف من قطبين يمثل احداهما قطعة العمل والقطب الثاني قطب من التنكستن عند جهد حدد من دائرة مفتو حة حسب موقع المعدن في السلسلة الكهروكيميائية ، وبعدها تم زيادة الجهد ب (±١٠٠) ملي فولت، اذعند كل ١٠ ملي فولت يتم زيادة التيار ، وأن التيار الذي يؤدي الى زيادة في الجهد يمثل تيار التآكل ، وتم حساب معدل التآكل باستخدام معادلة تافل .ومن النتائج التي تم الحصول عليها وجد ان معدل التاكل للعينات الملحومة بطريقة TIG اعلى من معدل التاكل بطريقة الخلط الاحتكاكي وقد تم تحسين هذا الارتفاع باستخدام الطريقتين معا وبنسبة ٣. ١٤%. وقد اعطت طريقة لحام الخلط الاحتكاكي اقل معدل تاكل مقارنة بالمعدن الاساس.