Artificial Aging Time Effect on Fatigue stress for Friction Stir Welded AA6061T6

تأثير زمن التعتيق الصناعي على مقاومة الكلال لسبيكة المنيوم AA6061T6 لحمت بلحام الخلط الاحتكاكي

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Abstract

This work involves studying the effect of heat treatment on the fatigue stress of friction stir welded joint of 6061T6 aluminum alloy. The microstructure , micro hardness , tensile and fatigue test of the welds and base alloy were examined before and after heat treatment which includes solution heat treatment at 500ºC and artificial aging at 190ºC for 2, 4, and 8hrs.The friction stir welding was carried out by using CNC milling machine at constant tool rotational speed of (1000 rpm) and welding speed of (20mm/min),the fatigue test is investigated for all specimens to obtain the S-N curve. The results show that the heat treatment decreased fatigue strength for all elements comparing with base metal, while ageing at 2 hrs gives the best fatigue strength due to participated phases.

Key words: Friction stir welding, 6061 Al-alloys, fatigue strength , solution heat treatment.

الخلاصة

تضمن البحث دراسة تأثير المعاملات الحرارية على مقاومة الكلال لوصلات لحام الخلط الاحتكاكي لسبيكة المنيوم 6061-T6 تم فحص البنية المجهرية والصلادة المايكروية واختبار الشد والكلال للوصلات قبل وبعد المعاملة الحرارية التي تضمنت تسخين العينات الى درجة حراره 500ºC ثم التبريد السريع بالماء ثم اجراء تعتيق صناعي حيث تم اعادة التسخين الى درجة 190ºCحرارة لفترات زمنيه 2,4,8 ساعة والتبريد بالهواء. انجز لحام الخلط الاحتكاكي على ماكنة التفريز المبرمجة باستخدام عدة تدور ١٠٠٠دورة بالدقيقة وسرعة لحام 20 m/mine تم تطبيق اختبار الكلال على جميع العينات التي تم تصنيعها من وصلات لحام الخلط الاحتكاكي وفق المواصفة القياسية ASTM قبل وبعد المعاملة الحرارية للحصول على منحني العمر (S-N) curve ومن النتائج التي تم الحصول عليها وجد ان المعاملات الحرارية تقلل من مقاومة الكلال للعينات الملحومة مقارنة بالمعدن الاساس وان افضل مقاومه للكلال كانت عند زمن تعتيق ٢ ساعه بسبب الاطوار المترسبه.

Introduction

Aluminum alloys are widely used for high-strength and light mass structures in aerospace and automotive applications. Aluminum−magnesium−silicon (Al−Mg−Si) denoted as 6xxx series alloys are medium strength, heat treatable alloys , have good formability from simple to complex profiles by extrusion and corrosion resistance [1][2].

A great number of problems related to the welding of aluminum and its alloys occur because of the oxide layer, hydrogen solubility, electrical conductivity and thermal characteristics; they all result in crack sensitivity (both solidification and liquation cracking), porosity, and heat affected zone (HAZ) degradation. 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 Fig. (1)

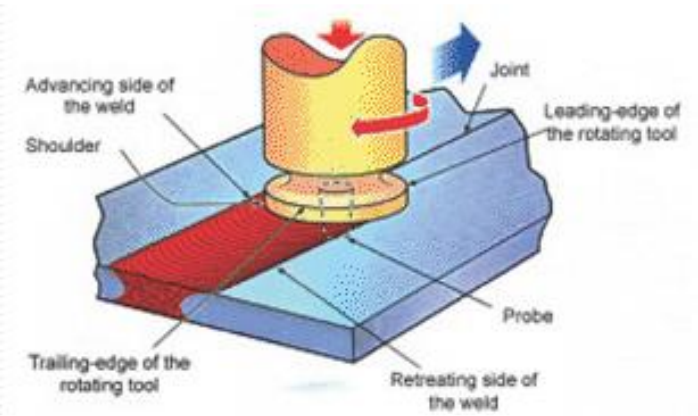


Fig. 1 a Schematic of the FSW and tool geometry[4]

FSW is depend on the welding parameters such as pin rotation speed, travel 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 [3][4]

The properties of various aluminum alloys can be altered by specific designated heat treatment. Some aluminum alloys can be solution treated to increase their strength and hardness. The heat treatment process can be classified into two processes; including solution heat treatment and artificial aging. This consists of heating the alloy to a temperature between 460^0C and 530^0C at which the alloying elements are in solution and water quenched then preheating to a temperature that investigate artificial ageing which generally carried out at temperatures up to approximately 200^0C (for 6000 alloys between 160 ^{0}C and 200^0C). Recently, some studies have been conducted on Friction Stir Welded joints after a heat treatment to evaluate the stability of the fine grain structure at high temperature. One interesting details is the presence of Abnormal Grain Growth(AGG) in the nugget. The occurrence of this phenomenon may be a problem if it leads to a decay of mechanical properties of the weld [5].Therefore, studying the mechanical properties and related significant factors would be important [6] Although tensile test is the most popular type of material test, fatigue strength is very important from the viewpoint of strength design because most of the fracture of practical machine members is due to fatigue fracture fatigue is a problem that effected any structural component or part that moves. Automobiles on roads, airplanes principally the (wings) in air, ships on the high sea constantly battered by waves, nuclear reactors and turbines under cyclic temperature conditions, and many other components in motion are example in which the fatigue behavior of a material assumes a singular importance. It is estimated that 90% of service failure of metallic components that undergo movement of one form or another can be attributed to fatigue. If there is, in a mechanical component, a discontinuity such as a sudden change in cross section, a fillet, hole, groove, or notch, high localized stresses are induced at such places. Such discontinuities are called stress raisers and the localized stress effect produce stress concentration. Stress concentration must however considered if the component is subjected to fatigue loading [7]

Many researchers study the stir friction welding for AA6061 - T6 on mechanical properties,

Yoshiaki Yamamoto[8] study the Fatigue Strength of Friction-Welded 6061 Aluminum Alloy Joints achieving that fatigue strength is decreased in friction stir welding method comparing with the base metal **.**

J.D. Costa and J.A.M. Ferreira. [9] studies the fatigue strength of friction stir welds and fusion inertly gas methods applied to AA6082-T6 under constant and variable amplitude loading and analyses the validity of Miner's rule for these specific welding conditions finding that FSW specimens present higher fatigue resistance than specimens welded by metal inert gas and tungsten inert gas processes. However, they still have lower fatigue lives than the base metal. Using the equivalent stress calculated by Miner's rule, a good agreement was observed between constant and variable fatigue loading results. The characteristic curve obtained for friction stir welds is higher than the International Institute of Welding (IIW) fatigue class for fusion welds with full-penetration both-sided butt joints.

Benachour Mustapha [10]studies the effect of the heat treatment or the state of material on the fatigue crack growth rate. The results show the influence of the heat treatment state on the shift of the fatigue life curves according to the propagated length.

The aim of this work is to investigate the effect of post-welding heat treatments on mechanical properties of butt FSW joints in6061T6 aluminum alloys.

Experimental Work

Material Selected:

The base metal used in this work was 12mm thick AA6061-T6aluminum alloy plate, whose chemical composition is provided by using (Thermo ARL 3460,optical Emission spectrometer). The results, which is compared to the American standard, are summarized in Table (1)

Table (1) Chemical composition analysis of 6061 Al T6 – alloy [11]

Element wt%	Mg	Si	Fe	Mn	Cu	Cr	Zn	Al
Measured value	1.03	0.778	0.6	0.14	0.82	0.09	0.03	Rem
Slandered value	0.8-1.2	0.4-0.8	Max 0.7	Max 0.15	0.15-0.4	0.04-.35	Max 0.25	Rem

Welding Process:

As shown in Figure (2), the samples of 200mm*70mm*12mm were longitudinally butt welded using CNC milling machine (type Bridgeport). All similar welds of 6061-T6 aluminum alloy were performed using a welding tool made of tool steel .The welding tool is composed of shoulder of (20mm diameter) and probe of (10mm diameter and 11mm length). The welding tool is rotated at high speed and plunged into the joint line between two plates to be butt welded together. In this study, the welding parameters such as tool rotation speed of (1000 rpm) and travel or welding speed of (20mm/min) .

Figure (2) Friction stir welding process

Categorizing of weld joint specimen

After completing welding process, the joints categorized to groups as listed in **Table (2).**

Table (2) Categorizing of weld joint specimen

Specimen symbol	state
A	As received
B	As welded
C	Solution heat treatment & artificial aging for 2h to weld joint
D	Solution heat treatment & artificial aging for 4h to weld joint
E	Solution heat treatment & artificial aging for 8h to weld joint

Heat Treatment

Precipitation heat treatment includes solution heat treatment and artificial aging were made for aluminum alloy AA6061-T6 welded joints in electric furnace at temperature of 500ºC for 30min. Quenching in water then was followed by artificial aging process at 190ºC for 2, 4, and 8hrs then cooled by air (ASTM Handbook,1991).

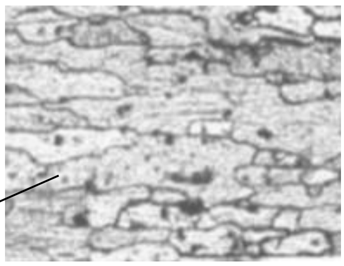
Examination and tests

1-Microstructure test

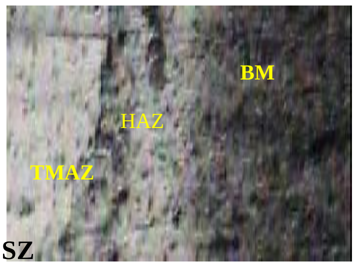
Samples made from a cross section of the FSW joints and base alloy were prepared including: ground, polished and etched and observed under optical microscope in sequences steps. Wet grinding operation with water was done by using emery paper of SiC with the different grits of (220,320,500, and 1000). Polishing process was done to the samples by using diamond paste of size (1μm) with special polishing cloth and lubricant. They were cleaned with water and alcohol and dried with hot air. Etching process was done to the samples by using etching solution (Keller's reagent) consisting of 95 ml distill water, 2.5 ml HNO3, 1.5 ml HCl and 1 ml HF washed after that with water and alcohol and dried in oven.

The friction stir welded joint samples were examined by Nikon ME-600 optical microscope provided with a NIKON camera, DXM-1200F.the microstructure results are shown in **Fig. (3)**

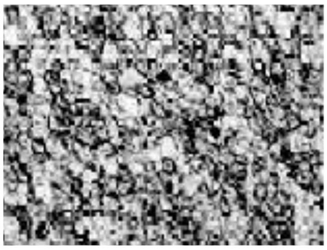
Mg_2Si



Specimen A

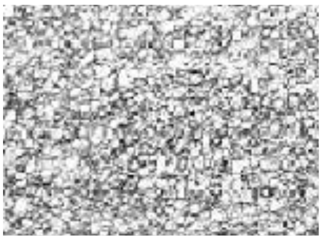


Speceimen B FSW zone



Specimen C in stir zone

Specimen D in stir zone



Specimen E in stir zone

Fig (3) the microstructure of all specimens in Table(2) at (40X)

Mechanical properties

2- Hardness test

The Vickers hardness instrument with a 300gf load was used for hardness profile across the friction stir weld joint where the results are shown in **Fig. (4).**

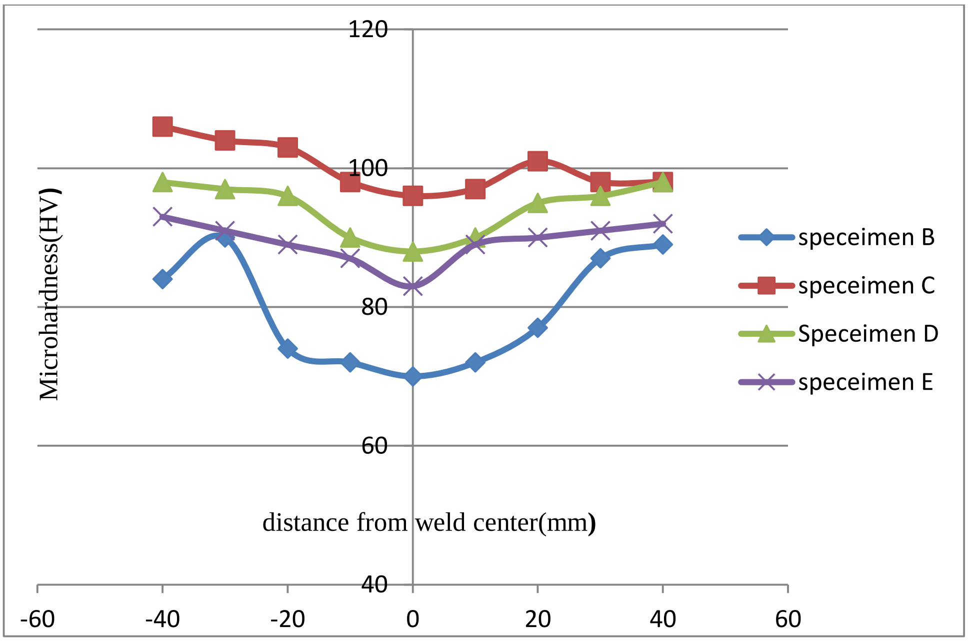


Fig. (4): The VickersHardness profiles of a transverse cross section welds zone

3- Tensile test

Tensile test was implemented for specimens prepared in the dimensions which is shown in **fig.(5)**according to ASTM176000 by using Testing machine smart series with preload value (N) 100 and cross head speed (mm/min) or rate. 20. Extension or position measured by XHD _ 100(XHD 100) for all specimens in **table (2)**, the obtained results are listed in table (4).

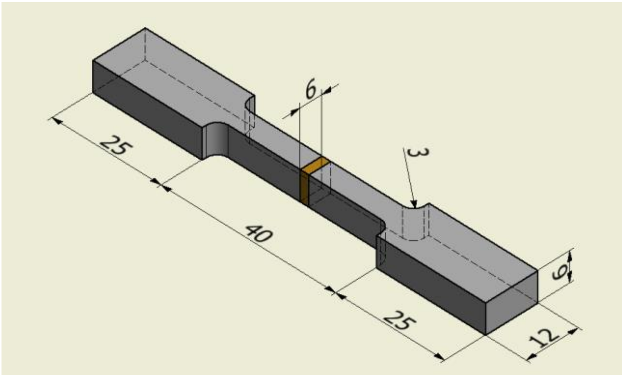


Fig. (5) Tensile test specimen dimensions (all dimensions in mm)

Table (3) Stander mechanical properties of 6061T6 [12]

Material	Yield strength MPa.	Ultimate tensile strength (UTS) MPa.	Percentage of elongation %
6061-T6	295	342	10

Table (4) results of mechanical properties

Sample	σu N/mm²	Yield stress σy N/mm²	Elongation %	Hardness Hv(kg\mm^2)
A	344	302	9	102
B	١٨١	٤٠1	6	70
C	218	180	10	96
D	177	115	10	88
E	81	40	2	82

5-Surface roughness

The average value of the free surface roughness, which was measured at the surface area of all specimens in table(2) indicated by the parameter Ra which is the center-line average of adjacent peaks results are listed in Table (5)

Table (5) the results of Surface roughness

Specimen Symbol	A	B	C	D	E
Surface roughness Ra (μm)	0.18	0.13	0.09	0.12	0.095

Rotating Bending Testing

To get perfect dimensions of the specimens and to avoid mistakes, an accurate profile 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 and to minimize residual stresses. The test specimens are shown schematically in Figure (6).

A rotating bending fatigue – testing machine was used to execute all fatigue tests, The specimen was subjected to an applied load from the right side of the perpendicular to the axis of specimen, developing a bending moment. Therefore, the surface of the specimen is under tension and compression stresses when it rotates.

The bending stress (σ_b) is calculated using the relation:

$$\sigma_b = \frac{p*L*32}{\pi*d^3} \quad (1)$$

where P is the load measured in Newton (N), and (L) the force arm is equal to 125.7 mm and(d)is the minimum diameter of the specimen in mm. The Test machine is Avery 7305 type and Fig.(7) shows the fatigue behavior of all specimens aluminum alloys 6061T6

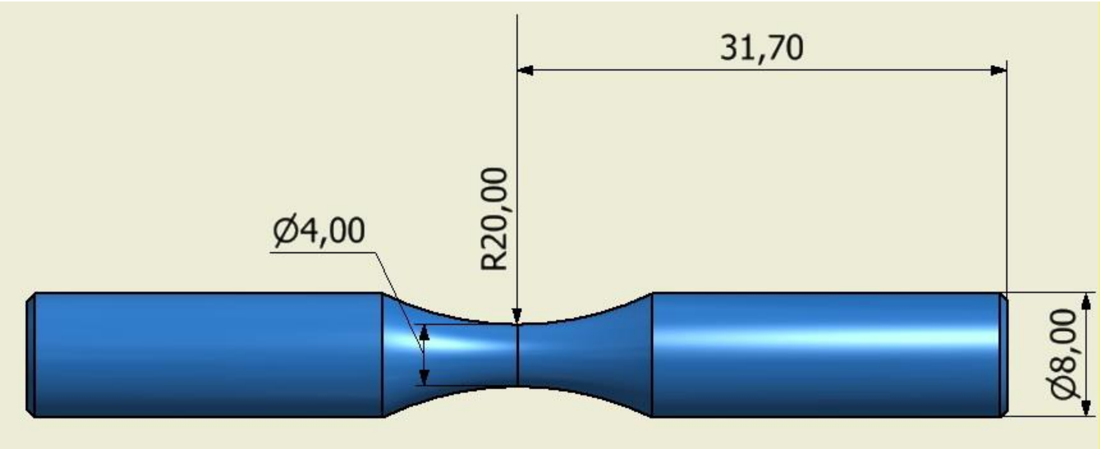


Fig. (6) Fatigue test specimen in mm

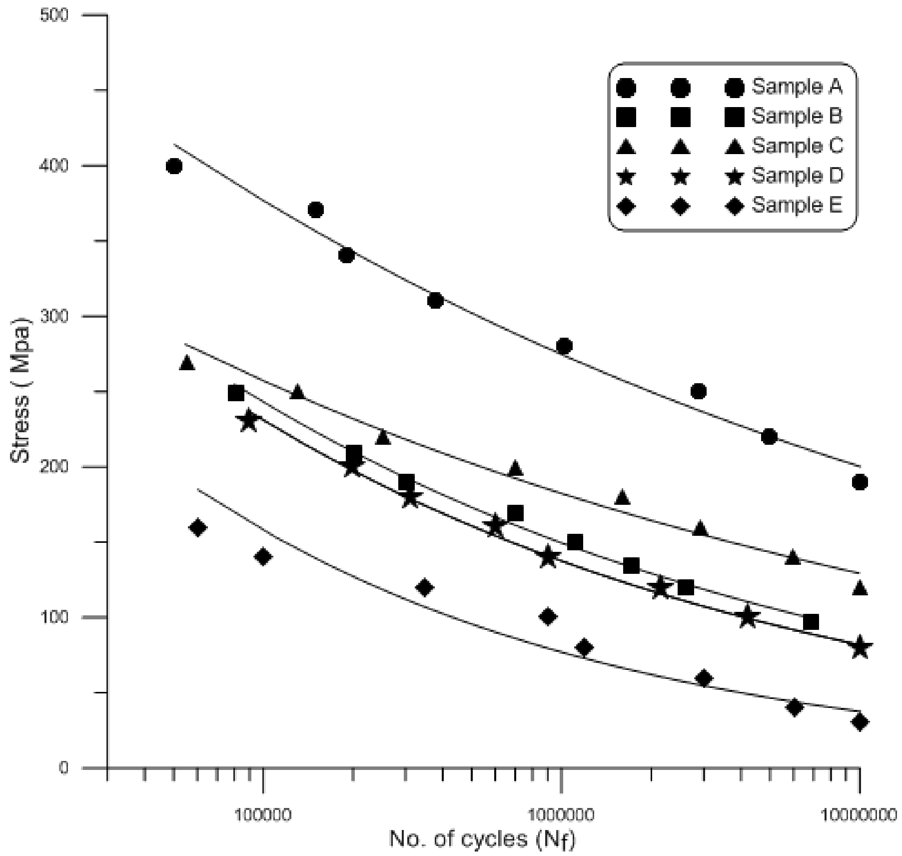


Figure (7) S-N curve of all specimens alloy 6061T6

The behavior may be described by the S-N curve equations as follows for all specimens

Specimen A $\sigma_f = 1749\, Nf^{-0,13}$

Specimen B $\sigma_f = 2287\, Nf^{-0,2}$

Specimen C $\sigma_f = 1356\, Nf^{-0,14}$

Specimen D $\sigma_f = 2946\, Nf^{-0,22}$

Specimen E $\sigma_f = 4467\, Nf^{-0,29}$

Discussion

In **Fig.(3)** specimen(A)shows the microstructure of base metal aluminum alloy 6061T6 contains coarse and elongated grains with uniformly distributed very fine precipitates . Found that the higher strength of the base metal was mainly attributed to the presence of alloying elements such as silicon and magnesium. These two elements combined together and underwent precipitation reaction and form a strengthening precipitate of Mg_2Si. As the result, the fine and uniform distribution of these

precipitates throughout the aluminum matrix provides higher strength to these alloys [13]. While a comparison between the base metal and fraction stir zone indicating by FSW we can see in sample (B) During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and equiaxed recrystallized grains . At the same time, after severe plastic deformation a fine, equiaxed grains due to the temperature difference between the tool shoulder side and base size and the tool centerline and the edge of the weld nugget which causes the grain size variations, this can be attributed to the mechanical forces operative during welding which causes both refinement and re – alignment of the matrix grains and should be beneficial with respect to various mechanical properties [14]

It also can be observed from **Fig.(3)** that variation in grain size of the alloy (6061-T6) depend mainly on the proportion of the silicon and magnesium elements in the alloy and the presence of the other alloying elements causing the forming of different soluble or insoluble compounds in solid state [15] . And also It had been observed that the aging time would have sufficient time to occur. The kinetics of phase precipitations are usually affected by the variations in aging time and heating temperature, this behavior can be attributed to the difference in microstructure of the specimens (C,D,E) [16]. The variations in the hardness measured across the welded specimens from the weld center towards the base metal are shown in fig. (4). In FSW processes specimen (B) the over aging 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 (70Hv) and generate a region of relatively low hardness value (78 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 [17].Hardness a gain increases toward the base metal (100Hv). 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 and when we compare this result with sample (C,D,E) In table (4)we see the specimen group (C) gives the high result compared with the specimens group (B, D,E) which gives the least value and the base metal exhibits the best mechanical properties and the well-defined proportional limit. A reduction of tensile properties to weld metal specimen found in a percentage of 47% (specimen B) comparing with base metal while specimen (C) obtained a 36 % reduction of the strength with respect to the base metal and specimens D,C gives the highest reduction due to over-aging, when welding a 6061-T6 alloy is a fairly well-understood phenomenon and it is explained in terms of the precipitation sequence undergone by this alloy with temperature [9].

The experimental of fatigue tests have allowed recording the life of specimens of 6061-T6 alloys welded by friction stir welding and base metal at different loading conditions.

Fatigue life was calculated based on the average of five values, as presented in Fig (7). Theoretical analyses and experimental evidence revel that the fatigue crack was initiated in the HAZ and then propagate into the weld metal to finally cause the failure. During the tests FSW welded specimens have been failed exactly in HAZ. [10]. The deformation and yielding are concentrated in the weld metal region in the case of lower strength for all weld specimens(B,C,D,E) compared with base alloy. The results of fatigue tests, which report compared fatigue strength of welded and parent metal (fig. 7), show rather reduced values of fatigue resistance for welded specimens. It is interesting to notice that, in spite of the fact that tensile tests generally gave rise to a fracture in the HAZ, all the welded fatigue specimens fractured in the stir zone, starting from outer surface.

Conclusion

1- Grain refinement in weld metal has been achieved due to frictional heating and plastic flow.

2- In FSW operation, hardness of weld zone is low comparing with base alloy because of the plastic deformation and cooling rate.

3-Tensile strength of welded joints of 6061-T6 Al alloy, undergo a remarkable reduction of the initial value.

4-Fracture in tensile tests is located in the HAZ; on the contrary, fatigue test specimens fractured in the welded metal in all cases. Fatigue fracture in the welded specimens occurred earlier than in the un welded specimens, due to the presence of some porosity.

5- 2 hrs of artificial ageing improved fatigue strength for the weld joint due to precipitated ages ,on contrary 4 and 8 hrs decreased the strength because of grain growth

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