Investigation of fatigue life of 6061-T6 aluminum alloys welded by metal inert gas welding

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Abstract

*The present research aims to investigate the effects of Metal Inert Gas (MIG) welding process on the mechanical properties and fatigue life of AA 6061 T6. A series of experimental techniques has been conducted to evaluate the mechanical and fatigue life. metal inert gas (MIG) have been carried out on Rolled sheet of 12mm thickness to obtain many butt welding joints with dimensions of (200 *100* 12) mm and with geometry of single and double V at (70 ^{o}) and square using ER- 5356 as a filler metal and argon as shielding gas. The welded pieces were tested by X-ray radiography and Faulty pieces were excluded Welding joints were subjected to heat treatment including heating the joints in furnace to (150 °C) for one hour then air cooling to relief heating stress.All specimens subjected to Vickers hardness, tensile test and microstructure examination. The examinations were carried out to show the effect of MIG weld method on the joint microstructure. The fatigue test of the welds and base alloy were examined to obtain the S-N curve.Results showed a general decay of mechanical properties of MIG weld joint that is due to heat input during the welding process and low cooling rate.*

Key word: *aluminum alloys, MIG welding, mechanical properties, fatigue strength.*

دراسة عمر الكلال لسبيكة الالمنيوم (6061-T6) الملحومة بطريقة الغاز الخامل (MIG)

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الخلاصة

*يهدف البحث الى بيان تاثير لحام القوس الكهربائي المحمي بالغاز MIG على الخواص الميكانيكية ومقاومة الكلال لسبيكة المنيوم 6061 T6. تم استخدام صفيحتين من المعدن في لحام عدة وصلات تناكبية بالابعاد mm (200*100*12) بعد عمل زاوية لحام تحضيرية من جهة واحدة ومن جهتين مقدارها (70) درجة على شكل حرف (V) وبدون زاوية باستخدام سلك لحام 5356 والاركون كغاز حماية بعد عملية اللحام والتاكد من خلو الوصلة من العيوب من خلال فحصها بواسطة جهاز X-ray radiography اجريت معاملة حرارية تضمنت تسخين الوصلة في فرن كهربائي عند درجة حرارة (150 C°) لمدة ساعة ثم التبريد بالهواء بهدف ازالة اجهادات اللحام اجري اختبار صلادة عيانية ومكروية بطريقة فيكرز واختبار شد وفحص البنية المجهرية لبيان تأثير اللحام على الخواص الميكانيكية وطبق اختبار الكلال للحصول على منحني العمر. أظهرت النتائج تدنيا في الخواص*

الميكانيكية للعينات الملحومة مقارنة بالمعدن الاساس للخواص الميكانيكية بسبب كمية الحرارة الداخلة والتبريد البطيئ.

Introduction

MIG welding is also recognized by gas metal arc welding. It is a semi-automatic process by which the arc length and feeding of wire into the arc can be controlled automatically and operator skills required to positioning the gun at a correct angle and moving it along the seam at a controlled travel speed in the metal transfer depends upon modular and spray transfer positions.

In this process consumable flux cored continuous wire or metallic electrode of diameter 0.8-2.4mm wound in spool form is fed at a required present speed through a welding gun, it picks up electric current from copper contact tube which is electrically connected to the DC power source and a shielding gases like argon, helium, carbon dioxide, carbon dioxide-argon mixture, argon-helium mixture. Shielding gases are also use to cooled down the gun. MIG welding is use to increase productivity and consistency of quality **[1].**

Fusion welding processes provide a large amount of energy in order to melt the base metal and filler material. The thermal input directly affects the microstructure and thereby the mechanical properties of the welded joint which is comprised of two principal regions namely weld metal and heat affected zone (HAZ) **[2].**

The 6061 aluminum alloy is one of the most common aluminum alloys for heavy duty structures requiring good corrosion resistance, truck and marine components, railroad cars, furniture, tank fittings, general structures, high pressure applications, wire products and pipelines. Many of these applications involves variable loading, which makes very relevant the study of the fatigue behavior of this aluminum alloy. In particular, the study of the fatigue behavior of welded joints is of primordial importance since welds are intensively used for structural applications **[3].**

The fatigue strength of an aluminum plate material with welds is generally lower than that of the base metal. Such actors as stress concentrations and variations in physical and mechanical properties in the weld area contribute to that difference. Although fatigue must be considered in the design of many structures, the literature contains little fatigue data for weld ments in the newer alloys.

The fatigue assessment of welded joints, including those made of aluminum alloys, is based on the so-called S-N approach (Maddox, 1991). This approach, which is included in main structural design codes of practice, adopts a classification system for details, and proposes for each fatigue class an experimental-based S-N curve, which relates the applied stress range (e.g. nominal, structural, geometric) with the total fatigue life.

Alternatively to this S-N approach, the Fracture Mechanics has been proposed to assess the fatigue life of the welded joints. It is very often claimed that welded joints have inherent crack-like defects introduced by the welding process itself. Therefore, the fatigue life of the welded joints may be regarded as a propagation process of those defects. A relation between the Fracture Mechanics and the S-N approaches is usually assumed. The slope of the S-N curves is generally understood to be equal to the exponent of the power relation governing the fatigue crack propagation rates of fatigue cracks **[3]** and **[4].**

To improve the mechanical properties and microstructural characteristics of these alloys this joint must be an interesting to alternative, since only a single welding pass is required to weld plates of 12.7 mm in thickness, reducing thus the heat input during welding which in turn reduces the microstructural transformations in the HAZ and enhances the mechanical properties of the welded joints. In terms of fatigue behavior, the effect of the welding profile in MIEA 6061-T6 aluminum alloy welds has been reported **[5].** Many studies investigate the mechanical behavior of welded joints:

Mustafa Kemal Kulekci [6] studied, the mechanical properties of welded joints of 6061-T6 aluminum alloy obtained with friction stir welding (FSW) and conventional metal inert gas welding (MIG). FSW welds were carried out on a semi-automatic milling machine. The performance of FSW and MIG welded joints were identified using tensile, fatigue, hardness, and impact tests. The obtained joints with FSW and MIG processes were also assessed for distortion that accompanied the welding processes. Taking into consideration the process conditions and requirements, FSW and MIG processes were also compared with each other to understand the advantages and disadvantages of the processes for welding applications of studied Al alloy. Better tensile, fatigue, and impact strength were obtained with FSW welded joints. The width of the heat affected zone of

FSW was narrower than MIG welded joints. The results show that FSW improves the mechanical properties of welded joints.

Aendraa Azhar Abdul Aziz [7] studied the effects of different filler alloys such as (ER5356 ER4043) toward Mechanical properties and microstructure of welded AA6061 aluminum alloy using gas metal arc welding. Single V butt joint configuration has been used for joining the plate's 6 mm thick plates using 21–22 V arc voltage. Tensile test was carried out .The results showed that the yield strength of base metal were 330 MPa while the yield strength of ER5356 joints and ER4043 joints were 200 MPa and 235 MPa, respectively. He clear that the difference properties of strength in both weld metal was due to the difference major element in the both filler composition. The amount of silicon content in ER4043 (Al-Si5%) filler is believed to play a role in the mechanical strength on weld metal. Microstructural examination was carried out using a light optical and electron microscope. The different filler alloys give different weld metal microstructure.

Omar bataineh[8] Studied the main factors that have significant effect on weld joint strength through factorial design experiments. The factors that were studied are arc voltage, filler feed rate, gas flow rate, specimen edge angle and preheat temperature. Results of factorial design experiments and the analysis of variance showed that arc voltage and filler feed rate are the only significant factors of the other. Optimal settings of arc voltage and filler feed rate were reached using regression analysis at 24 V and 7 in/s, respectively, at which the mean weld strength is maximum.

S. Jannet [9] made Comparison between of friction stir welding and fusion welding of 6061-T6 and 5083-O aluminum alloy based on mechanical properties and microstructure Properties .FSW and Fusion Welded processes were also compared with each other to understand the advantages and disadvantages of the processes for welding applications of the Al alloy. The mechanical properties of welded joints of 6061 T6 and 5083 O aluminum alloy obtained using friction stir welding (FSW) with four rotation speed (450, 560, 710 and 900 rpm) and conventional fusion welding The performance of FSW and Fusion welded joints were identified using tensile, hardness and microstructure. Findings: Better tensile strength was obtained with FSW welded joints. The width of the heat affected zone of FSW was narrower than Fusion welded joints welded joints

In this study the influence of MIG weld processing on mechanical properties and fatigue strength were investigated on aluminum alloy 6061 T6 weld joint.

Experimental Work

1-Metal selection

The composition of the used alloy is shown in table **(1),** by using ARL Spectrometer.

Table (1): Chemical Analysis of the used metal 6061- T6. [10]

Elements w%	Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
Measured value	0.6	0.4	0.3	0.12	1.0	0.2	0.18	Rem.
Standered value	0.4-0.8	Max 0.7	0.15-0.4	Max 0.15	0.8-1.2	0.04-0.35	Max 0.25	Rem.

2- Welding process

Two Pieces of 12mm thick plates aluminum alloy 6061-T6 were machined to the required dimensions (200 *50 *12) mm and with geometry of single and double V at (70^0) and square as shown in Fig.**(1).**The plates were cleaned before the welding procedure with a scraper and acetone then they were butt welded (two pass for each side) using the MIG process.

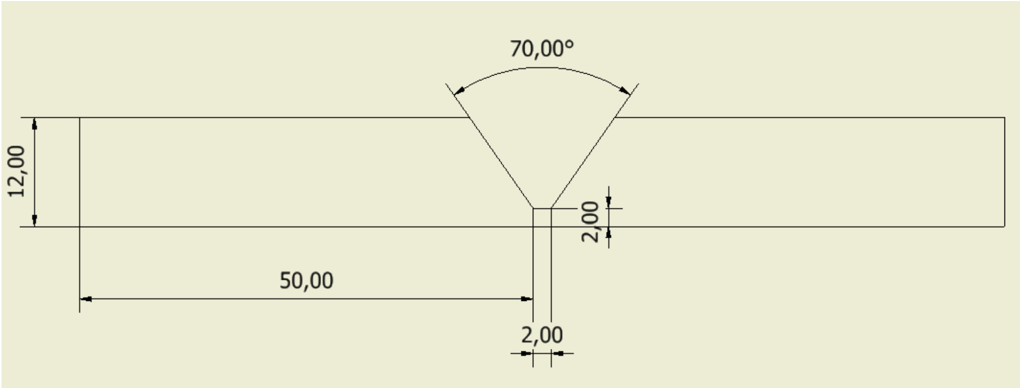
In the MIG welding process, a suppermig-460 type semiautomatic welding machine was used for welding the plates with parameters shown in table **(2)** using argon as shielding gas at a flow rate of (10L/min), and ER 5356 of 1.2 mm diameter as a filler material its chemical composition is shown in table **(3)**, with a welding speed of (10 mm /sec) was used to carry out the MIG welds.

Table (2): Welding parameter of MIG welding.

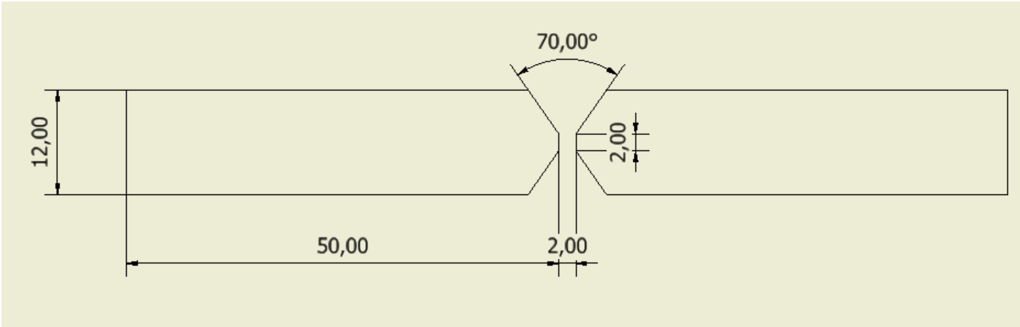
symbol	Current (A)	Voltage (v)	Travel speed (mm/s)	Flow rate L/min	N0.pass	Wire diameter (mm)
B	140	25	220	10	2	1.2
C	110	25	220	10	3	1.2
D	120	22	220	10	3	1.2

$$Heat\ \ Input = \frac{543 \times I \times V \times 60}{S} \text{ --------------------------- (1)}$$

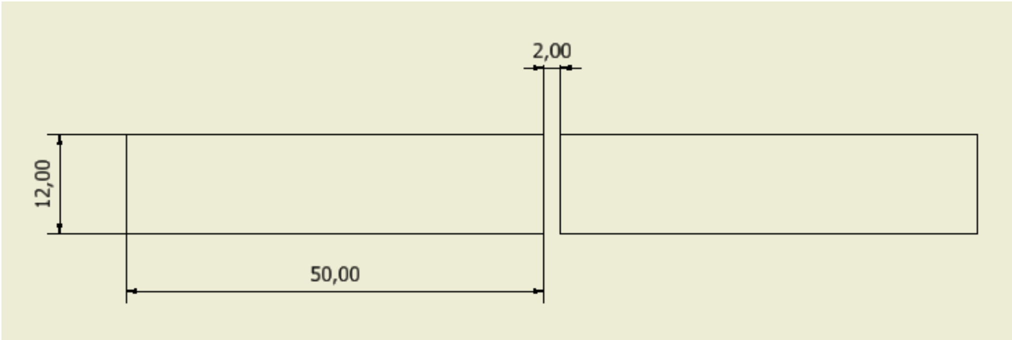
All welded pieces were tested by X-ray radiography and Faulty pieces were excluded. The joints without defects used to prepare many specimens for tensile and fatigue test.



Sample (B)



Sample (C)



Sample (D)

Fig (1) The dimension of butt welding joint.

Table (3): Standard Chemical Composition of ER5356 Welding Wire [11].

Elements w%	Mg	Mn	Si	Br	Ti	Cu	Cr	Zn	Fe	Al
Nominal value	4.5–5.5	0.05–0.20	0.25 % Max	0.0008 Max	0.06–0.20	0.10	0.05 –0.20	0.10	0.4	BAL
Actual value	4.9	0 .1	0.22	0.0007	0.09	0.1	0.1	0.1	0.4	BAL

3- Preparation of specimens

Many specimens for tensile test were prepared from weld joint and base metal by dimensions according to DIN 176000, as shown in Fig.**(2a)** and fatigue test specimen as shown in fig **(2b)** and to get perfect dimensions of a fatigue specimen and to avoid mistakes, an accurate profile should be attained. All specimens were manufactured using programmable CNC lathing machine by writing a suitable program from the profile of specimen on an edge of metallic plate.

Then, all the specimens were machined, corresponding to that profile during manufacturing of specimens, careful control was taken into consideration to produce a good surface finish and to minimize residual stresses.

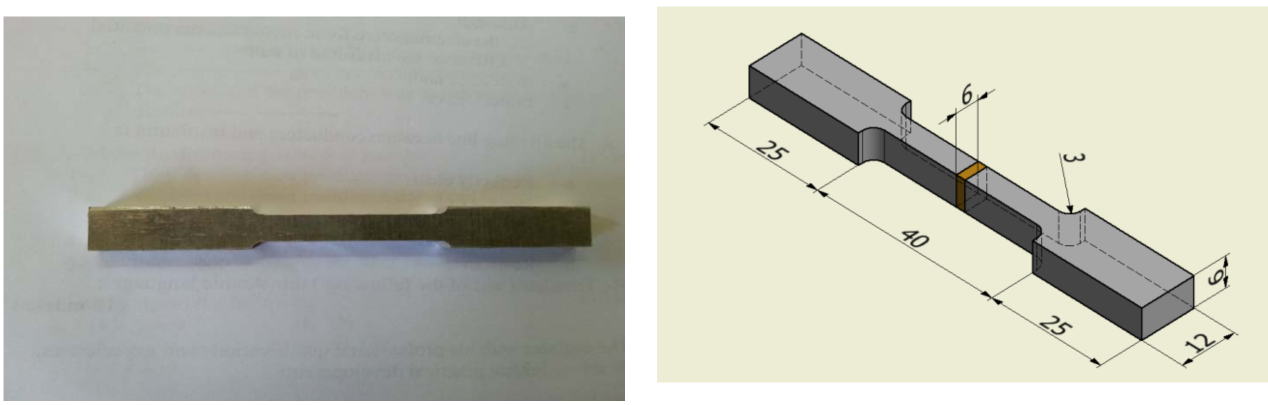


Fig.(2a) tensile test specimen dimensions in mm

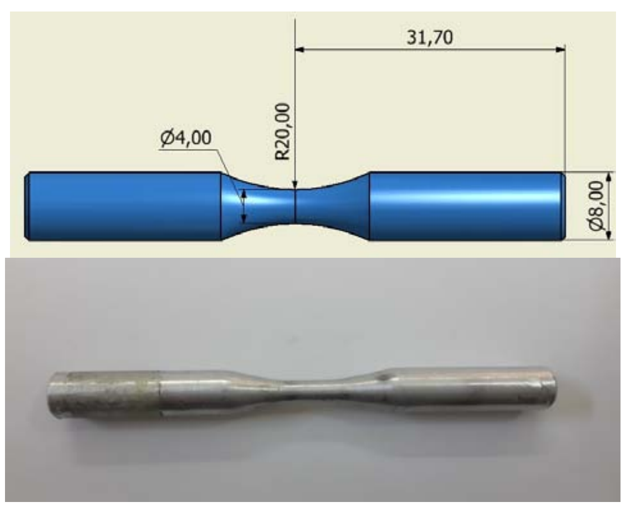


Fig (2b) Rotating-Bending Machine Test Specimen
Fig (2) The dimension of specimens test.

4-Categorization of weld joint

After completing the specimen, they were categorized to groups as shown in **table (4).**

Table (4): Categorizing of specimens used in this study.

symbols	Condition
A	As received
B	Butt joint with single V angle 70°
C	Butt joint with double V angle 70°
D	Square Butt joint (angle 90°)

5-Surface roughness

The average value of the free surface roughness, which was measured at the surface area of all specimens in table **(4)** indicated by the parameter Ra which is the center-line average of adjacent peaks by using perthometer type (S6p) results are shown in table **(5).**

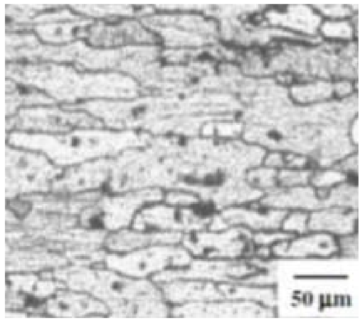
Table (5) the results of Surface roughness

Specimen symbol	Surface roughness Ra (μm)
A	0.18
B	0.13
C	0.09
D	0.12

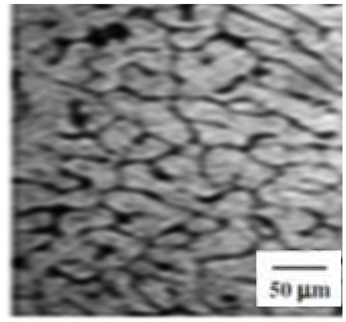
6-Microstructure test

Micro structural changes from weld zone to the unaffected base material were examined with optical microscope. Specimens were prepared for microstructure test including wet grinding operation using emery paper of SiC with different grits of (120,320,500, 800 and 1000). Polishing process was done by using diamond paste of size (2.5μm) with special polishing cloth. They were cleaned with water and alcohol then dried with hot air dryer.

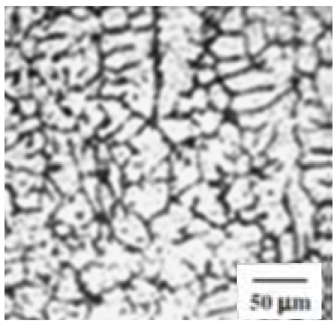
Etching for the structure by use Keller's reagent consisting of 95 ml distill water, 2.5 ml HNO_3, 1.5 ml HCl and 1 ml HF then washed after that with distill water then dried with hot air dryer. The welded joint samples and base metal were examined by Nikon ME-600 computerized optical microscope provided with a NIKON camera, the examined result was shown in Fig**. (3).**



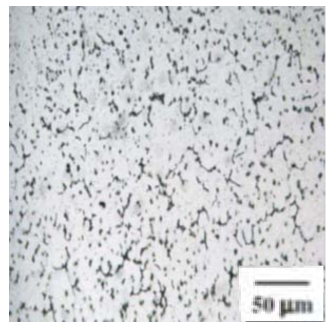
Sample (A)



Sample (B) W.M



Sample (C) W.M



Sample (D) W.M

Fig (3) The microstructure of all specimens in Table (3).

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 gm load for 15 sec. Fig. **(4).**

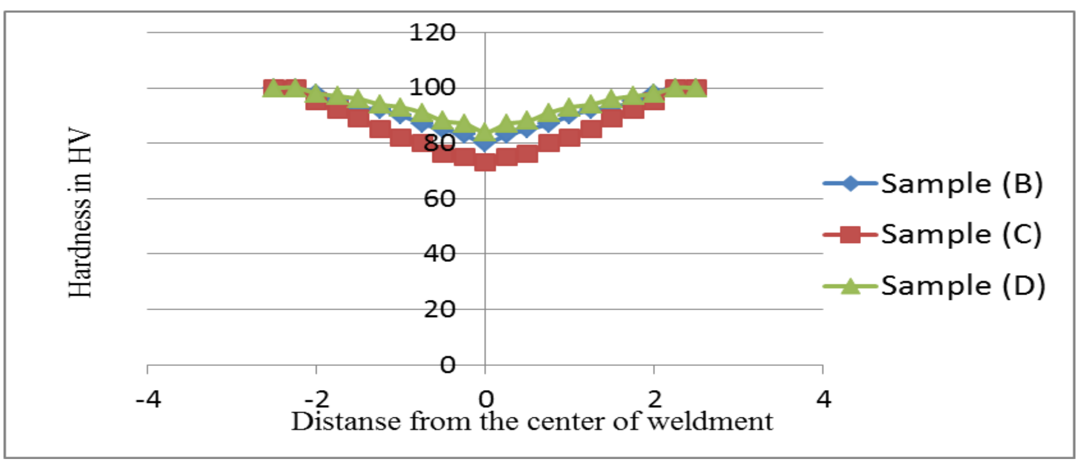


Fig.(4) Micro hardness distributed result for all specimens.

Tensile test

Tensile test was implemented for all specimens, using metallic materials tensile test united device, the obtained results are shown in table **(6)** and the relationship between stress and strain are shown in **Fig.(5).**

Table (6): Results of mechanical properties.

Sample	σu N/mm²	Yield stress σy N/mm²	σ_F N/mm²	Hardness Hv (kg\\mm^2)
A	344	246	172	125
B	192	158	110	80
C	189	176	123	70
D	201	180	126	84

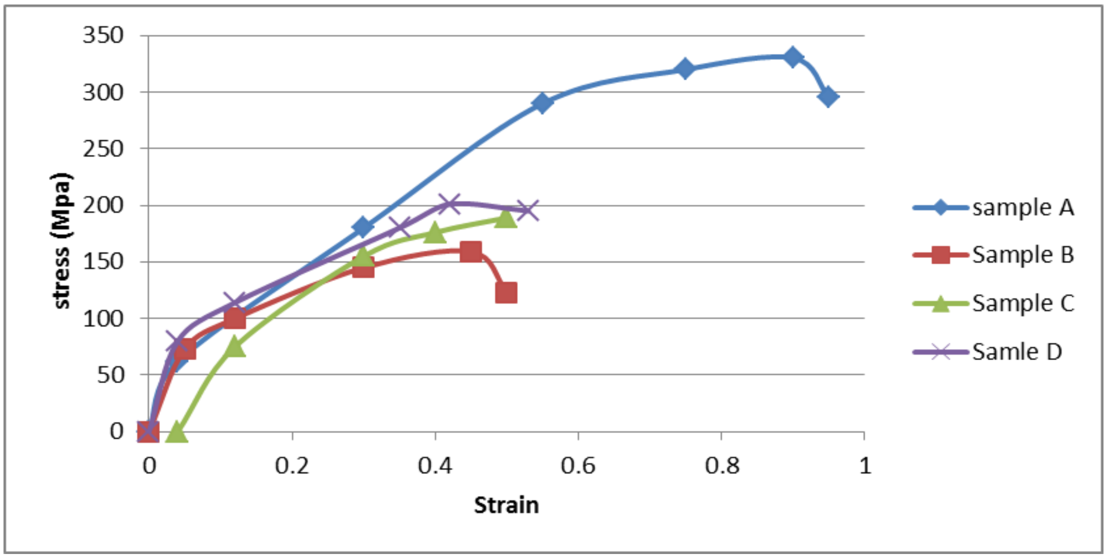


Fig. (5) Relationship between tensile stress and strain for all specimens.

Rotating Bending Testing

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 (S_b) is calculated using the relation: [12]

$$\sigma_b = \frac{p * L * 32}{\pi * d^3} \quad \text{-------------------------- (2)}$$

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 which is shown in Fig. **(6)** and Fig**.(7)** shows the fatigue behavior of all specimens aluminum alloys 6061T6.

The behavior may be described by the S-N curve equations as follows for all specimens (A, B, C, D) respectively:

$\sigma_f = -8E\text{-}05\ N_f + 307.51$ ---------------------------- (3) – (A)

$\sigma_f = -5E\text{-}05\ N_f + 210.62$ ---------------------------- (4) – (B)

$\sigma_f = -4E\text{-}05\ N_f + 225.54$ ---------------------------- (5) – (C)

$\sigma_f = -4E\text{-}05\ N_f + 229.24$ ---------------------------- (6) – (D)

Fig. (6) Side view of Avery 7305 Fatigue testing Machine.

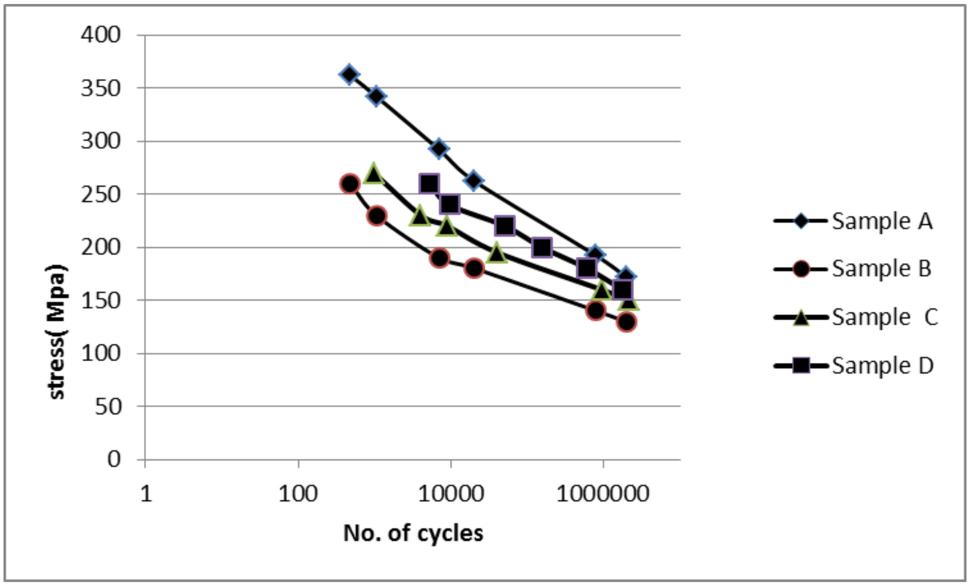


Fig. (7) S-N curve of all specimens alloy 606..1T6.

Table (7): List of symbol.

symbol	Title	Unit
I	welding current	Ampere
V	welding voltage	volt
S	welding speed	m/min

Discussion

Fig**.(3)** shows the micro structure based metal and weld region of AA 6061T6. The base metal microstructure sample (A) contains coarse and elongated grains with uniformly distributed strengthening precipitates (Mg_2Si.). The higher strength of the base material is mainly attributed 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. The high Magnesium content is responsible for good weld ability **[13]**

The fusion zone of MIG method represented by symbol (B, C, D) give the Lower amount of strengthening precipitates compared to the base metal specimen symbol (A). Therefore, the Strengthening of (Mg_2Si**)** precipitate is weak in MIG and contain dendritic structure this may be due to intense heat input and shielding gas.of the base metal and fast cooling of molten metal. . The microstructure and grain size affects the mechanical properties of material.

Hardness in the fusion zone for specimens (B,C,D)Table (6) have the lowest value due to the coarse dendritic grains; inter dendritic segregate phases and the lack of strengthening phases of the microstructure **[13].** Usually the microstructure and the mechanical` properties of an aluminums alloy will change after the welding because of the melting of the base material during the welding process. To overcome this problem, a heat treatment is applied to the welded part to obtain the good mechanical properties and to release the residual stress on the part **[14].**

Fig. **(4),** Indicates the cross-sectional hardness profile from retrieving side metal through center of the weld to advancing metal at a constant welding speed for welded region. The base metal exhibits the best mechanical properties and the well-defined proportional limit. The tensile properties of the sample (D) obtained a 26.8% reduction of the ultimate strength it respect to the base metal and weld metal respectively. The microscopic test give the reason of it .The deformation and yielding are concentrated in the weld metal region in the case of lower.

The experimental of fatigue tests have allowed recording the life of specimens of 6061-T6 alloys welded by MIG 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 MIG welded specimens have been failed exactly in HAZ. [14]. The deformation and yielding are concentrated in the weld metal region in the case of lower strength for all weld specimens (B,C,D) compared with base alloy where specimen B gives 36% reduction percentage and other specimens gives a reduction value of 28%. 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 melted zone, starting from outer surface.

Conclusions

1- Hardness change in the welded material is affected by the amount of the heat input during the welding process.

2- Tensile strength of welded joints of 6061-T6 Al alloy, under the experienced welding conditions, undergoes a remarkable reduction of the initial value. The residual strength of the welded joint is around 37.57% of the parent metal.

3- Fatigue strength of the butt joint with single V angle 70° has a reduction percentage of 36% comparing with the base alloy while the Butt joint of double V angle 70° gives a reduction of 28%

4-In the HAZ tensile strength reduce to (190) Mpa and hardness to (90) HV compared to based.

5-In most of the experienced cases, fracture in tensile tests is located in the HAZ; on the contrary, fatigue test specimens fractured in the WM in all cases.

6- Fatigue fracture in the welded specimens occurred earlier than in the un welded specimens, due to the presence of some porosity and to reduced mechanical properties (tensile strength and toughness) in the WM.

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