Development the Mechanical Properties of (AL-Li-Cu) Alloy

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ABSTRACT

The aim of this research is to develop mechanical properties of a new alloy aluminum-lithium-copper which is prepared by casting under control atmosphere in a permanent metal mold. The mechanical properties (impact, elasticity modulus, tensile strength, and fatigue) with microstructure were examined before and after heat treatment. The research outcome showed that the modulus of elasticity of the prepared alloy is higher than standard alloy about 2%. While the alloy that was heat treated for 6 h and cooled in water, showed a higher ultimate tensile stress comparing with as-cast alloy. The homogenous heat treatment gives best fatigue behavior compared with as-cast and other heat treatment alloys. Also, the impact test illustrates that the homogeneous heat treatment alloy gives the highest value.

Keywords: aluminum-lithium alloys, heat treatment, microstructure, mechanical properties

تطوير الخواص الميكانيكية لسبيكة ألمُنيوم– ليثيوم– نحاس

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الخلاصة

الهدف من هذا البحث هو تطوير الخواص الميكانيكية لسبيكة جديدة من ألمُنيوم- ليثيوم- نحاس. هذه السبيكة حضرت بطريقة السباكة بقالب معدني دائمي تحت ظروف جوية مسيطر عليها. تم فحص التركيب المجهري وأجريت الفحوصات الميكانيكية للسبيكة قبل وبعد المعاملة الحرارية لدراسة تأثير المعاملة الحرارية على خواصها الميكانيكية والتي تتضمن: معامل مرونة، مقاومة الشد، مقاومة الصدمة، وجهد الكلال. وقد بينت النتائج زيادة في معامل المرونة للسبيكة المحضرة مقارنةً مع السبيكة القياسية بمقدار 2% تقريباً. بينما أعطت السبيكة المعاملة حرارياً لمدة 6 ساعات ومبردة بالماء مقداراً أعلى لمقاومة الشد الأقصى مقارنة مع السبيكة قبل المعاملة. إن السبيكة التي أجريت عليها معاملة المجانسة أعطت سلوك كلال أفضل مقارنة مع السبيكة قبل المعاملة والسبائك الأخرى المعاملة حرارياً. أيضاً إن فحص الصدمة بيّن إن السبيكة المعاملة حرارياً بطريقة المجانسة قد أعطت أعلى قيمة.

الكلمات الرئيسة: سبائك ألمُنيوم- ليثيوم، معاملة حرارية، خواص ميكانيكية، التركيب الداخلي.

1. INTRODUCTION

Aluminum-lithium (Al-Li) alloys have inherently desirable properties such as increased specific stiffness and strength. Aircraft designers have been searching for lightweight metallic materials with good strength for use in structural applications since the beginning of the aviation era. The most attractive reason for alloying with Li is the beneficial impact on stiffness and weight reduction. For every 1 wt% addition of Li, the elastic modulus is increased by 6% and the density is reduced by roughly 3%, **Prince**, **2013**. In addition, since aluminum by itself is a lightweight metal, there are only a few choices for alloying additions for further weight reduction. On the periodic table, Si, Be, Mg, and Li are the primary metals with a lower density that could be alloyed with Al. Of those four metals, only Mg and Li have good solubility. However, alloying with Mg tends to produce alloys with lower stiffness and increased corrosion susceptibility, **Starke** and **Staley**, **1996**. On the other hand, Li metal is the lightest metallic element, has increased solubility at high temperatures, and upon ageing produces fine precipitates that increase strength and stiffness, **Kumar**, **et al**., **1991**. These characteristics make Li metal as the ideal alloying candidate.

Any alloy of typical components with low-density structural members can be used in aerospace, vehicle skins, airframes and liquid oxygen and hydrogen fuel tanks in spacecraft. The advantages of Al-Li alloys include relatively low densities, excellent fatigue, cryogenic strength high elastic modulus, toughness properties, and superior fatigue cracks growth resistance. The last property is a key factor for damage-tolerant aircraft design. A jagged crack path through the material increases the resistant to fatigue crack growth due to a large amount of roughness under tension dominated loading. Unfortunately, loading conditions that contain compressive overloads, that flatten the crack surfaces, reduce crack closure and cause crack growth rates to be accelerating. Another disadvantage of these alloys is the desired heat treated conditions; the mechanical properties are often highly anisotropic for example depressed ductility and fracture toughness in the short transverse direction. Another problem is a very high crack growth rate for microstructural short cracks, which could mean relatively early cracking in high-stress regions like rivet holes, **Tayon**, **2012**.

Although (AL-Li) alloys have many limitations as for specific stiffness, stability at high-temperature and high cost (three times more than conventional aluminum alloys), it has many advantages over composite materials and economically, hybrid materials can be up to 10-30 times more expensive than AI-Li alloys. **Peel**, **1986**.

Comparing, AI-Li alloy fabrication technology with other metals manufacturing methods like sheet forming, forging and extrusion, they offer higher ductility and fracture toughness to obtain finished product. **Nair**, **et al**., **1985** and **Jackson**, **1989**. By precipitation heat treatments method, AL-Li alloys strength are increased as those used for conventional Al-alloys, with little difference. Only if cold-work is done before precipitation treatment enhances peak strength for many Al-Li alloys. Also, alloy elements, such as zirconium (Zr) is added to control the grain microstructure during heat treatment. Replacement alloy (AA 7075-T6) instead of (AA 2090) gives 8% lower density and 10% higher stiffness than conventional alloy that is used heavily in aircraft structures but the former Al- alloy gives superior corrosion resistance in the salt-spray environment than (AA 7075-T6).

Alloy (AA 2091) was developed instead of (AA 2024-T3). It gives 8% lower density and 7% higher modulus as well as superior damage tolerance. Alloy (AA 8090) was developed as a substitute for some of the longest serving of the commercial aluminum alloys, namely (AA 2014) and (AA 2024). Alloy (AA 8090) has 10% lower density and 11% higher modulus than the conventional one, at cryogenic temperatures (AA 8090) shows superior mechanical properties **Venkateswara**, and **Ritchie**, **1992**.

Tan and **Sheppard**, **1987** joined microstructure and properties of extrusion processing to Al-Cu-Li alloy (AA 2091), using homogenous temperature as a standard. Extrusions were done with a range of temperature compensated strain rates. In different aging temperatures, a series of curves were obtained for both stretched 2% and unstretched specimens, **Yong-Lai**, **2007** showed the relationship between the hot deformations and strain rate of a new Al-Cu-Li-Mg-Zr alloy and its microstructure by using the Gleeble-1500 thermal-mechanical simulator. At the same deformation temperature with the increase of the strain rate from 0.001 s^{-1} to 10 s^{-1}, the peak value of actual stress is elevated, then with the same strain rate, the peak value of the actual stress diminished with the increase of the deformation temperature from 360℃ to 520℃.

In this study, a direct comparison of the cast prepared Al-Li alloy with that of the heat treatment alloys. The objective was to characterize the main features of these alloys. This study also is aimed to study the tensile and fatigue behavior, in relation to the microstructural change. The test data were compared with previous literature showing that the prediction based on the developed work is very acceptable.

2. EXPERIMENTAL PROCEDURE

2.1 Alloys Preparation

Under controlled atmosphere alloys melting and casting in a permanent metal, the mold was done as shown in **Fig. 1**. Because of the high affinity of Li to oxygen, great care must be taken during any process that involves heating the alloy. Therefore, in this work, it was wrapped with aluminum foil before melting, and then the molten alloy was poured and cast under control atmosphere with argon gas in a specially designed permanent mold as recommended in reference, **Sauermann et al., 2006**. **Table 1** shows the weight percentage of the alloying elements compositions as cast prepared in this work compared with some of the most important alloys. The chemical composition of the alloys, which were cast, was analyzed by a spectrum analyzer. The samples were cast as bars and sheets as shown in **Fig. 2**.

2.2 Microstructure Specimen Examination

The following steps were used to prepare the specimen for microstructure images:

1. First is cold mounting, which was used manually with an acrylic polymer resin (pink).
2. Preparing grinding equipment contains SiC abrasive in a resin bond for soft, non-ferrous materials in the HV 40-150 hardness range, using a liquid (water) as a lubricant and step by step the pressure is reduced when the paper becomes finer.
3. Polishing all the samples with 30 μm then 6 μm diamond 2P3 cast polish fluid. Repeatedly, using lubricants to maintain the samples. An optical microscope was used to check progress in removing scratches.
4. Etching for 5 seconds with Keller's reagent (0.5HF - 1.5HCl - 2.5HNO_3 - 95.5H_2O) was used. Then etching was repeated until the grain boundaries were clearly seen.
5. At different magnification rate of an optical microscope to examine microstructure. Images of different grain morphologies, inter-dendritic/cellular regions and any defects, such as pores, cracks, oxides strings were obtained. The microscope was used in this work is beam engineers (rmm-7t 2003-1200x).

2.3 Alloys Heat Treatments

Heat treatment was conducted to samples to investigate the effect of heat treatment. They were immersed in a salt solution at 470ºC for 30 minutes and 6 hours. Some of the specimens were cooled in the furnace and the others were cooled by water. The age hardening was used by heating some samples for 8 hours at 177ºC. Heat treatment as homogeneous was performed to the other samples at 530ºC for 18 hours. The muffle furnace which was used for heat treatment of prepared alloy is shown in **Fig. 3**, and the practical experiments were conducted at Al-Mustansiriyah University - College of Engineering Lab.

2.4 Tensile, Impact and Fatigue Tests

The tensile, toughness and fatigue specimens for the test were cut to dimensions recommended in ASTM E8/E8M–11, (ASTM E-23) and ISO 10328 respectively. **Fig**. **4** shows tensile, impact and fatigue tests specimens.

The static tensile test was performed at Technical College in Baghdad by Zwick/Roell computerized device, the tests performed at room temperature with relatively low deformation rate (2 mm/min) to ensure pure tensile force applied to the specimen. The impact test was conducted as a Charpy V-notch test (simply supported beam test) by HECKERT device. The fatigue test was carried out as a torsion fatigue and conducted at Al-Mustansiriya University-College of Engineering Lab, the device which was used is HI-TECH. **Fig**. **5** shows the images of the mechanical tests devices. All mechanical properties tests were recorded as the average values for three to five specimens.

3. RESULTS AND DISCUSSION

3.1 Microstructure Examinations

The light optical microscope was used to examine the microstructural variations. **Fig**. **6** illustrates the microstructures of the specimen of Al-Li alloy specimen as-cast (without heat treatment) in two different zones. It is not clearly crystals and δ-phase defined since these specimens are not heat treated or age hardened. However, the hygroscopic property of element Li causes porosity and cracking are illustrated in this figure. It is known that these alloys exhibit an unusual fusion boundary cracking phenomenon that is associated with an equiaxed grain zone that forms via a solidification mechanism in alloys containing precipitates of Li and Zr. This is because the combination of Li and Cu in the interface liquid lowers the eutectic temperature of the liquid and is responsible for the hot cracking problem **Lee et al**., **2016**. The evolution of the microstructure for heat treatment specimens is demonstrated in **Fig**. **7**. **Figure 7-a** shows heat treated specimen for a half hour and cooled by water. The time is very short for this heat treatment; therefore, the microstructure is not much different with microstructure as-cast specimen. While the heat-treated specimen for (6 hours) and cooled by water is clear crystal identify with precipitate the δ-phase. Due to the specimen was cooled by water the size of the crystal is fine, as shown in **Figure 7-b**. The difference between the microstructure of specimen which was cooled in the furnace and the previous specimen which was cooled by water is only in the size of the crystals that are larger, as well as more precipitating the δ-phase as shown in **Figure 7-c**.

Significant changes in the microstructure of homogeneous heat treated specimen, are shown in **Fig**. **8**. The crystals are coarser also a little bit more precipitating the δ-phase compared with heat treated samples for 6 hours and cooled by the furnace.

Continuous precipitation of δ-phase (Al_3Li) from a supersaturated solution in position of specific location involve the age hardening of Al-Li alloys

3.2 Tensile Test

The mechanical properties of the tensile specimen were investigated in all samples. **Table 2** illustrates the values of the tested specimen compared with the standard Al-Li alloy (AA 8090-T3), which is the closest in terms of its components with the prepared alloy in the lab. Due to the increased lithium amount in the prepared alloy compared with the amount of the standard alloy, increase the modules about 2%, and this is in line with previously published research, such as the work by, **Romios**, **et al**., **2005**.

While clearly noticing that the ultimate tensile was decreased in its value for the heat-treated specimens than the standard alloy specimens from 335 MPa to 290 and 315 MPa for heat treated for 6 hours and cooled in the furnace, and heat treated for the same duration but cooled in water respectively. It is believed that the reason for the decreases the value of the ultimate strength due to lack of the heat treatment proper procedures. However, the evolution of the mechanical properties of heat-treated specimens significantly comparing with as-cast alloy specimen.

The amount of elongation of heat-treated specimens are lower than those of as-cast specimen, and the reason is due to the precipitation of the δ-phase (Al_3Li), which in turn prevents the movement of dislocations and thus will decrease dramatically the ductility.

3.3 Impact Test

In addition to the tensile test, the impact test was performed for a clear vision of mechanical properties of the prepared Al-Li alloy to provide a background on this alloy. The impact test is the criteria of the toughness to indicate the power absorption of the material. **Table 3** shows the results of this test for as-cast, heated for 1/2 h and cooled in water, heated for 6 h and cooled in water, heated for 6 h and cooled in the furnace, aging for 8 h at 177ºC, and homogeneous at 350ºC for 18 h. The highest value is 89 J for homogeneous specimen due to the highest amount of the precipitation of δ-phase in evolution alloy, and this is because the duration of the homogeneous heat treatment is very long (18 hours) allowing very fine particles of δ-phase to precipitate uniformly on the whole alloy.

Conversely, the as-cast alloy gives the lowest value in toughness because there is no good chance to improve the alloy by precipitation hardening. However, this toughness value is better than the toughness of the alternative aluminum alloys such as (AA 2024) or (AA 7075), which are both among the competitive alloys in the aviation and aerospace industries. Whenever evolution the alloy through heat treatment, the toughness has been improved gradually was clear from the values of the tests, which are listed in the table.

3.4 Fatigue Test

Torsional-fatigue tests were calculated and obtained at the low cycle and room temperature for four groups specimens; the 1st group was for as-cast alloy specimens, the 2nd group for heating for 6 h and cooling in the furnace, the 3rd group for heating for 6 h and cooling in water and the 4th group for a homogenous at 530ºC for 18 h. **Fig. 9** illustrates the fatigue life of the four groups as the load in N versus number of cycles, each point of the data was recorded as the average of five specimen tests. The first observation, there is not a significant variant of fatigue life between the four cases. The second observation is that the heat-treated alloy for 6 hours and cooled by water gives highest fatigue life regarding the tempered specimens because this alloy is better in terms of tensile strength. This is a well-known fact, there is a direct correlation between ultimate tensile strength and fatigue life; increasing tensile strength will increase the fatigue life and vice versa. Although, the load is less than 25 N the as-cast alloy failed in just above 4000 cycles because this alloy has lower tensile strength as indicated in **Table 2**.

There is a little bit improvement in fatigue life about 1000 cycles between the heat-treated alloy which were cooled in furnace compared with the as-cast alloy. The last observation from these curves is the fatigue life of homogeneous heat treatment, which is the best curve compared with alternative curves for those with temper specimens. An important feature of fatigue behavior in AI-Li alloys are the sharable nature of δ-phase (Al_3Li) strengthening precipitates, which results in inhomogeneous deformation and unusually tortuous (zigzag) crack path morphologies. Therefore, homogeneous heat treatment has a greater chance of increasing precipitation phase in the microstructure, which improves the fatigue life, This is in line with **Ritchie** and **Rao**, **1992**.

4. CONCLUSIONS

The following conclusions are drawn from this experimental work:

This study proved that Al-Li alloys have inherently desirable properties such as increased specific stiffness and strength especially when heat-treated. It is concluded that significant improvements have been made to this alloy to enable improved performance of next-generation aviation and aerospace industries.

The major findings of this study are summarized as follows:

1. It is required to understand the influence of chemical composition and microstructure on mechanical properties. Increasing the amount of lithium as an alloying element to aluminum up to solubility limit (4.2%) improved significantly the young modulus and ultimate tensile strength in addition to improvement of the toughness and fatigue.
2. Al-Li alloys are precipitation hardening, therefore the parameter of time and temperature in the heat treatment of these alloys influence significantly the microstructure evolution and mechanical properties due to the amount of precipitate of the δ-phase (Al_3Li) in structure.
3. Increasing time and temperature in heat-treated alloys improve ultimate tensile, toughness, and fatigue.
4. Heat-treated alloy for 6 h and cooled by water gives a higher value of tensile strength (315 MPa), while as-cast alloy gives lower strength (185 MPa).
5. Alloy with homogeneous heat treatment at 530ºC for 18 h gives a higher toughness (89 J) than other alloys.
6. The best behavior to fatigue live is with homogenous heat-treatment alloy for at 530ºC for 18 h.

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Table 1. The composition of Al-Li alloys (wt. %).

Alloy	**Cu** (%)	**Li** (%)	**Zr** (%)	**Others** (%)	**Al**
Prepared alloy (Cast)	1.5	3.0	0.1	1.0 Mg	Bal.
AA 2090*	2.4-3.0	1.9-2.6	0.08-0.15	0.0-0.25 Mg	Bal.
AA 2091*	1.8-2.5	1.7-2.3	0.04-0.16	1.1-1.9 Mg	Bal.
AA 8090*	1.0-1.6	2.2-2.7	0.04-0.16	0.6-1.3 Mg	Bal.
Weldalite 049*	5.0	1.3	0.1	0.4 Mg	Bal.

*** Venkateswara**, and **Ritchie**, **1992**

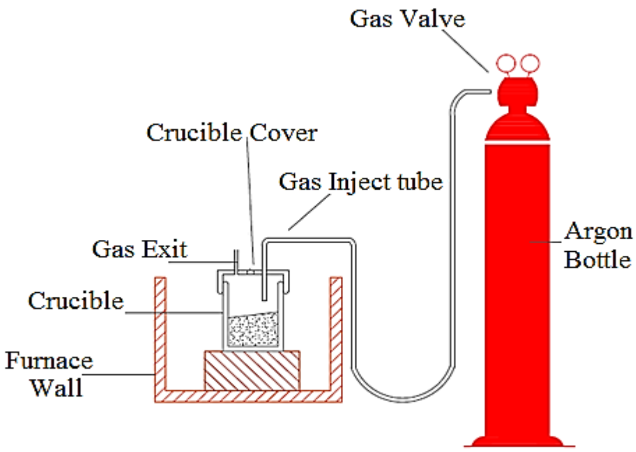
Table 2. Tensile test for Al-Li prepared alloys compared with standard alloy.

Mechanical properties	Young Modules (GPa)	Ultimate Stress (MPa)	Elongation (%)
Standard alloy AA 8090-T3	77	335	19
Prepared alloy as-cast	79	185	30

Heat treated (6 hours) cooling in the furnace	79	290	12
Heat treated (6 hours) cooling by water	79	315	8

Table 3. Impact test results.

As-cast alloy	Heat for 1/2 h and cooled by water	Heat for 6 h and cooled by water	Heat for 6 h and cooled in furnace	Aging for 8 h at 177ºC	Homogeneous at 530ºC for 18 h
65 J	68 J	75 J	70 J	85 J	89 J



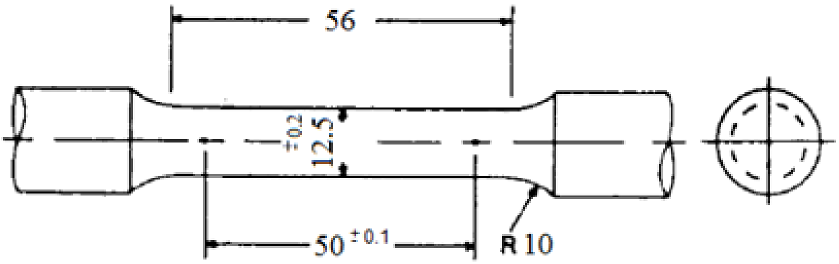
(a) Schematic diagram for furnace equipment

(b) Casting furnace and mold

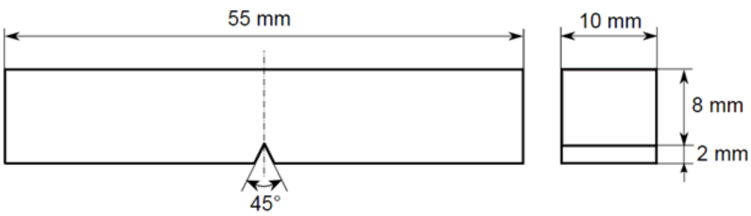
Figure 1. Casting equipment for preparing alloy.

Figure 2. Al-Li alloy casting samples as bar and sheet.

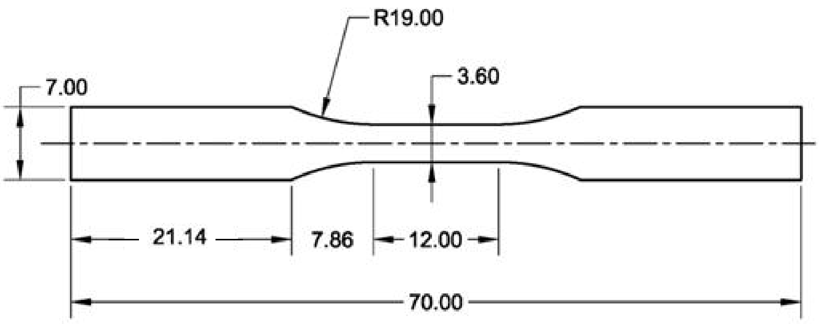
Figure 3. Heat treatment muffle furnace.



(a) Tensile test specimen dimension



(b) Impact test specimen dimension



(c) Fatigue test specimen dimension

Tensile specimen   Fatigue specimen

(d) Mechanical tests specimens' images

Figure 4. Mechanical tests specimens dimension and images.

(a) Tensile test device

(b) Fatigue test device

(c) Impact test device

Figure 5. Mechanical tests devices.

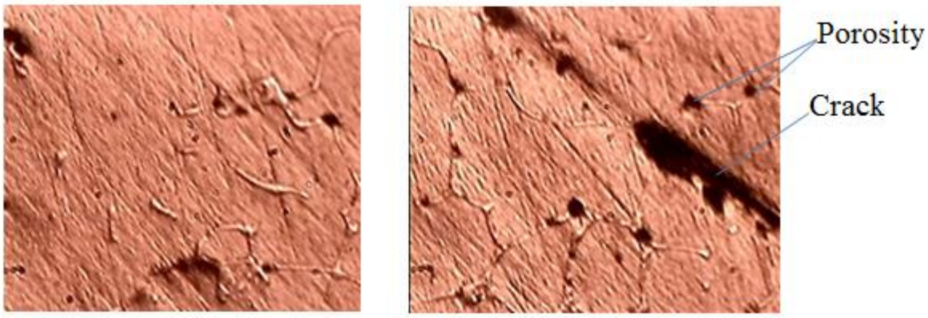


Figure 6. Microstructure images of Al-Li alloy specimens as cast 100x.

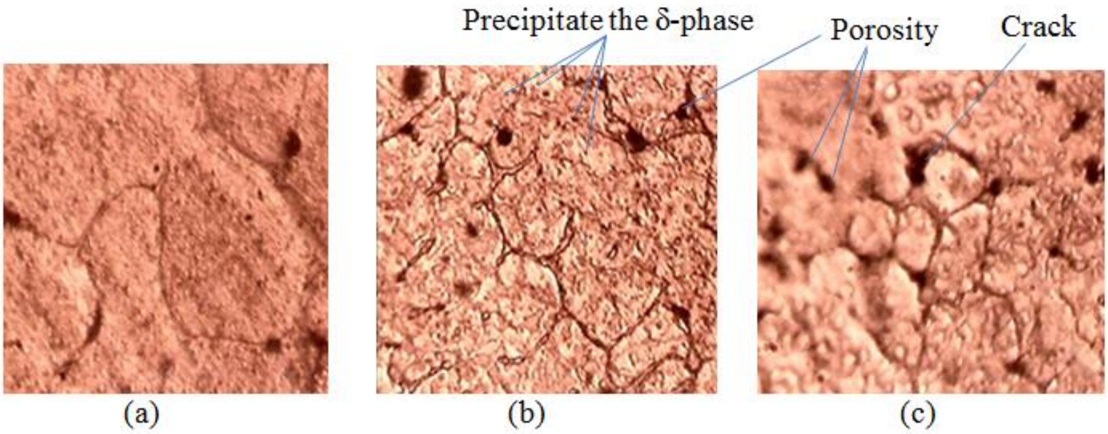


Figure 7. Evolution of the microstructure for heat treatment specimens 100x,
(a) heat treated for a half hour and cooled by water, (b) heat treated for 6 hours and cooled by water,
(c) heat treated for 6 hours and cooled in the furnace

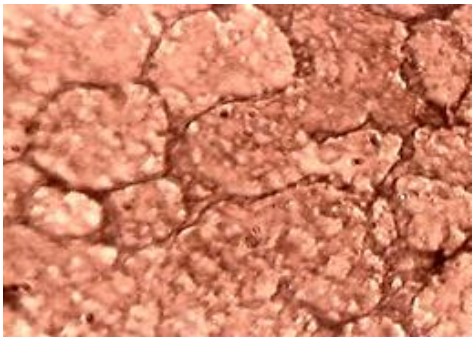
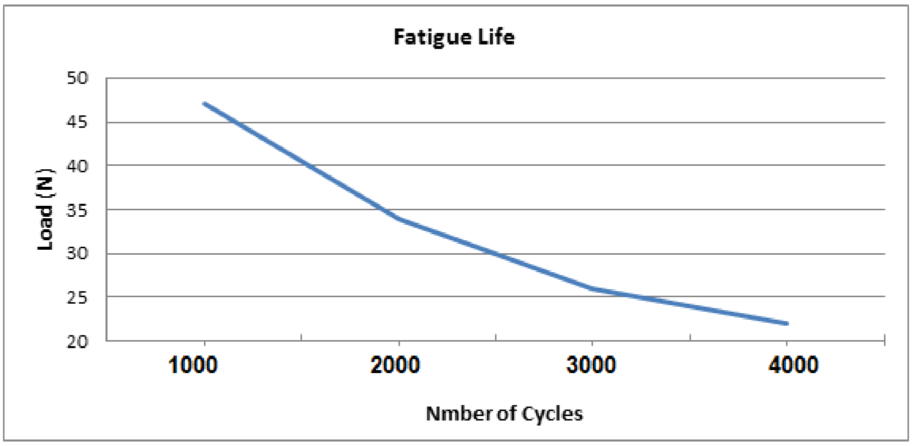
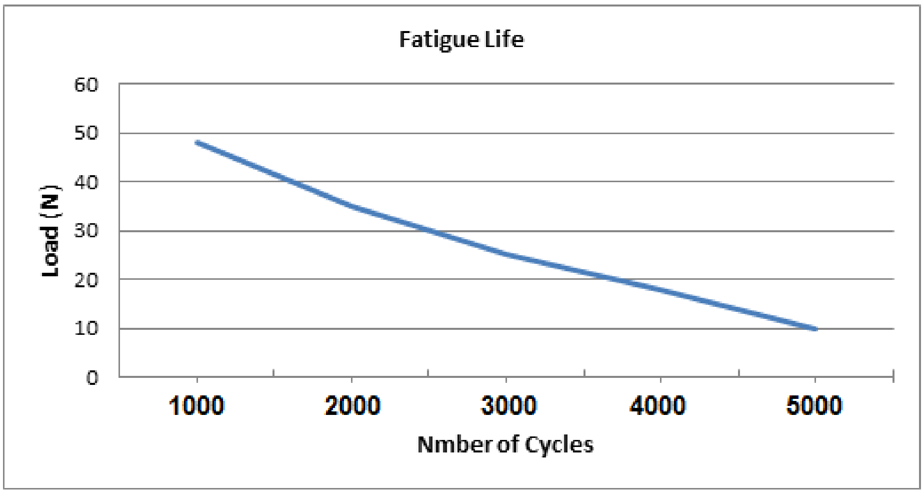


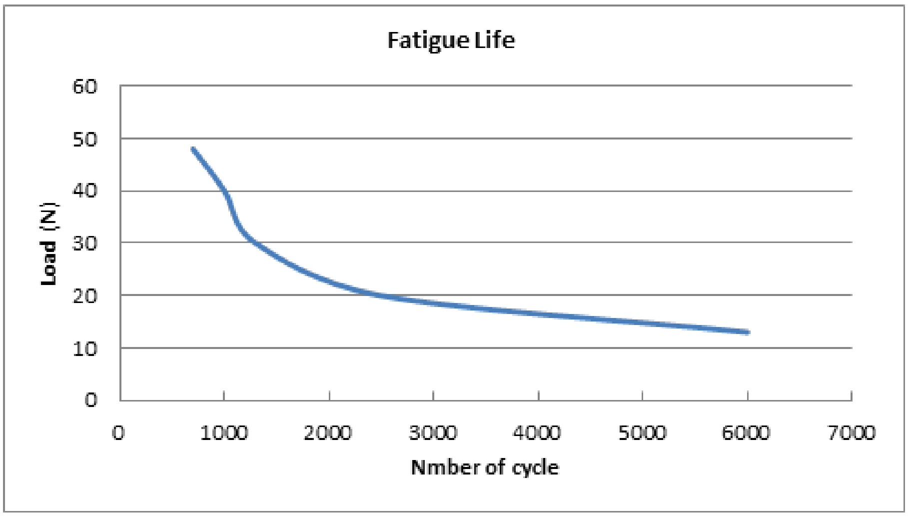
Figure 8. The microstructure of homogeneous heat treatment specimen 100x.



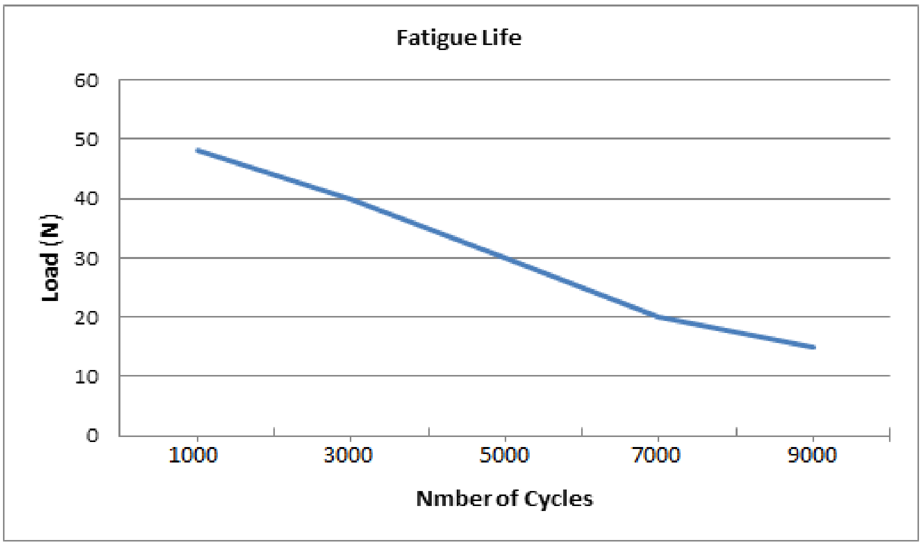
(a) as-cast alloy



(b) heating for 6 hours and cooling in the furnace



(c) heating for 6 hours and cooling by water



(d) homogenous heat treatment at 530ºC for 18 h

Figure 9. Fatigue tests for four cases heat treatment Al-Li alloys.