The Influence of Quenching Media and Aging Time on Microstructure and Mechanical Behavior of 6061 Aluminum Alloy

Naser Korde Zedin
Production Metallurgy Engineering Department , University of Technology/Baghdad
Email: Naserkorde_56@yahoo.com

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ABSTRACT

Aluminum-magnesium-silicon (Al-Mg-Si) alloys are medium strength, excellent formability, good corrosion resistance and widely used in extruded products and automotive body materials. The influence of quenching media with different aging time on microstructure and mechanical properties of 6061 aluminum alloy was investigated. The results show formation of (Mg_2Si) and ($CuAl_2$) phases when solution treatment was applied (at 520°C for 2h, followed by quenching in water and oil at room temperature then aging (at 175°C for 2, 4 and 6h)) which result improving of both the strength, hardness and decreases elongation. It can be noted that, the grains of samples which are quenching in water is finer than the structure of samples which are quenching in oil. The values of yield stress and ultimate tensile strength decrease respectively with increasing aging time to 6h as (258MPa) and (264MPa) for water quenching and (199MPa) and (235MPa) for oil quenching. In this piper were measured and discussed the variation of the yield stress, ultimate tensile strength and elongation with different solution quenching and aging time.

Keywords: 6061 Aluminum Alloy, Age Hardening, Precipitation Hardening, Mechanical Properties.

تأثير أوساط الاخماد وزمن التعتيق على التركيب المجهري والسلوك الميكانيكي لسبائك المنيوم 6061

الخلاصه

تمتاز سبائك (Al-Mg-Si) بمقاومتها المتوسطة وقابليتها العالية للتشكيل ومقاومتها الجيده للتاكل مما جعلها واسعة الانتشار في صناعة المبثوقات وهياكل وسائط النقل. في هذا البحث تم دراسة تأثير اختلاف أوساط الاخماد و زمن تعتيق على البنية المجهرية و الخواص الميكانيكية لسبائك المنيوم 6061. بينت النتائج تكون طوري Mg_2Si و $CuAl_2$ عند اجراء المعالجة المحلولية (بدرجة حرارة 520مْ لمدة (2 ساعة) والمتبوعة بالاخماد (مرة بالماء و مرة بالزيت) عند درجة حرارة الغرفة ثم التعتيق عند درجة حرارية 175 مْ لمدة (6,4,2 ساعة) مما ينتج تحسين في كلاً من المقاومة و الصلادة وتنخفض المطيلية. كذلك نلاحظ ان البنية المجهرية

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للعينات التي يتم اخمادها بالماء اصغر من البنية المجهرية للعينات التي يتم اخمادها بالزيت. قيم اجهاد الخضوع ومقاومة الشد القصوى التي تم الحصول عليها تقل بزيادة زمن التعتيق الى 6 ساعة ,القيم بالتتابع (258 ميكا باسكال) و(264 ميكا باسكال) للاخماد بالماء و (199 ميكا باسكال) و(235 ميكا باسكال) للاخماد بالزيت. في هذا البحث تم قياس و دراسة التغيرات التي تحدث على المعادن بواسطة دراسة مقاومة الخضوع ومقاومة الشد والمطيلية مع اختلاف محاليل الاخماد و زمن التعتيق.

INTRODUCTION

Aluminum-magnesium-silicon (Al-Mg-Si) denoted as 6XXX series alloys are medium strength heat treatable alloys and have excellent formability and good corrosion resistance characteristics [1]. Because of these favorable properties, the 6061 alloy is used in the transport and the public works domains (framework, pylon, handling equipment. . .) and also for complex structures assembled by welding [2].Mg and Si are the major solutes; they increase the strength of the alloy by precipitation hardening [3]. These materials can be heat treated to produce precipitation to various degrees. The as-obtained microstructure of the material is called T6 temper (tempering around 175◦C). The heat treatment process can be classified into two processes, including solution heat treatment and artificial aging. The 6XXX series alloys is including (T6) treatment involving solution heat treatment and subsequent artificial aging and quenching is a common method to increase the strength of the alloy [4]. Quenching hardening is a commonly used as heat treatment in manufacturing industry to increase the service reliability of components. The success of quenching process mainly depends on the heat transfer of the quenching medium[5,3]. The solution heat treatment is between 460 and 530°C at which all the alloying elements are in solution to obtain the supersaturated a solid solution. ‘‘Artificial aging’’, ‘‘age hardening’’ or just ‘‘aging’’ is obtained by heating to about 175°C(for 6000-alloys generally between 160 - 200°C [1]) for various amounts of time and leads to precipitation of various phases [3].When the material is subjected to a solution heat treatment followed by a quenching and a tempering treatment, its mechanical properties reach their highest level and become very good compared to other aluminium alloys. The heat treatment and precipitation hardness was studied by several groups [5–8]. Demir and Gunduz investigated the effect of artificial aging on the machinability of 6061Al alloy in as received, solution heat treated, and solution heat treated and aged conditions. Their results indicate that aging at 180°C for various times significantly affects the surface roughness of the workpiece[6]. Abdulwahab et al. have investigated the microstructural and mechanical properties upon thermal aging of a sand cast antimony-modified A356-type Al-Si-Mg alloy. The prepared alloy was solution heat treated at 540 ºC /1 hr then subjected to thermal aging treatment at 180ºC for 1-5 hr. From the results, the tensile properties and hardness increased with thermal ageing treatment. While the impact energy and elongation decreased upon ageing [7].

Doward and Bouvier compared several alloys of 6061-type investigating, in particular, the effect of the departure of Si content from the nominal one (excess Si/excess Mg) on the mechanical properties and the nature of fracture. They concluded that optimal combinations of strength and toughness are obtained from Si-lean and balanced chemistries [8].

Kim et al. investigated the mechanical and tribological properties of rheo-formed AA6061 wrought alloy, their results show that, peak hardness was obtained after 10 h of aging at 177 °C following solution heat treatment at 530 °C for 2 h and the surface roughness increases with the aging time [9]. In the present investigation, the mechanical properties of 6061 Al-alloy subjected to solution heat treatment followed by aging to various degrees are investigated and discussed in relation to the respective microstructural changes during heat treatment.

Experimental work

Materials

The study was carried out on 5mm thick flat plates of 6061 Al alloy, the plates were cut into samples of (10 mm width and 15 mm length) by electric cutting machine. In this study, the samples were analyzed by the Specialized Institution of Engineering Industries-Baghdad. The chemical composition is shown in Table (1).

Sample Preparation

The samples cut from the stander 6061 Al-alloy, then prepared for microstructure and hardness testing with dimensions (1.5cm length and 1.5cm width). The samples preparation achieved by grinding process to get facing free surface polished process and Etching process. The examination process was carried out by using optical microscope (Type, Nikon.120, Japan) with digital camera and computer. Other samples prepared for tensile testing depended on standard ASTM E8 as shown in Figure (1).

Aging treatment

A carbolite GLM3 model box furnace was used to heat the prepared samples. After heating was completed, the various samples were quenched in water and oil. Table (2) shows the two quenching media (water and oil) used during the experiment test. The samples in the as-received condition which were solution treated with water and oil at 520°C for 2h, then aging at different aging time (2,4 and 6h) at temperature 175°C as shown in Figure (2).

Hardness measurement

The hardness was measured after aging treatment using Vickers Hardness Testing Machines with 0.5 kg load. The Vickers hardness was measured in department production Eng. and metallurgy in technology university -Baghdad and the value reported is the average of three readings taken at different locations. The general equations applied for determined of Vickers Hardness Testing is [3,10]:

$$H.V = 1.8544 \times [\, P/(d_1+d_2/2)^2] \qquad \ldots (1)$$

Where:

H.V: Vickers Hardness.

P : Applied load kg.

d : Sample diameter (mm).

Results and discussion

Microstructure

The microstructure of 6061Al-alloy is shown in figure (3 and 4). The stable β phase Mg_2Si and $CuAl_2$ which is normal for 6061 Al-alloy. Specifically, the sequence formation of independent clusters of Mg and Si atoms formation of co-clusters that contain both Si and Mg. The needle-shaped β phase (Mg_2Si) has been observed to be the dominant intermediate phase in the Al–Mg–Si and Al–Mg–Si–Cu alloys at early stages of aging [11]. The stable β phase Mg_2Si and $CuAl_2$ distribution was examined by microscopic investigation on polished samples.

The predominant equilibrium second phases in 6061alloy are AlFeSi, $CuAl_2$ and Mg_2Si and the results of XRD test Figure (5) show this fact clearly. Addition of copper to Al–Mg–Si alloys refines the precipitate structure induces the formation of the meta-stable precursor Q' (AlMgSiCu), and increases the hardness [1]. The Figures (3 and 4) show the microstructure of the samples, it can be noted that, increasing the aging time causes increasing in the size of grans. Generally, the structure of samples which are quenching in water is smaller than the structure of samples which are quenching in oil as a result of high cooling rate which is obtained by water. Further increase in the aging time to 6 h at 175°C causes coalescence of the precipitates into larger particles [12,13].

Mechanical Properties.

Hardness

Figure (6) shows the hardness as a function of artificial aging time for the samples. The values of hardness were measured by performing at least three measurements for every aging condition and the results were averaged. The hardness of the 6061 Al-alloy, immediately after solution treatment and aging for 2 h is 58 kg\mm^2 (water quenching) and 48kg\mm^2 (oil quenching) but with increasing the aging time at 175°C the hardness of the samples will increase.

Maximum hardness was reached after approximately 4 h of aging at 175°C as 81 kg\mm^2 (water quenching) and 66 kg\mm^2 (oil quenching). 6061 Al-alloy used in this investigation contains 0.82 Mg, 0.73 Si and 0.29 Cu in weight percentage. Therefore, the increase in hardness after aging at 175°C for 4 h could be cooperative precipitation of $CuAl_2$ and Mg_2Si phase particles. An increase in hardness could be explained by diffusion assisted mechanism, and also by hindrance of dislocation by impurity atoms, i.e. foreign particle of second phase, since the material after quenching from 520°C (solution heat treatment) will have excessive vacancy concentration [6,14].Tash et al. investigated the effect of metallurgical parameters on the drilling performance of heat treated Al-alloys containing Mg and Cu in different proportions. They showed that aging at 175°C for 2 h resulted in an increase in hardness due to the coherency of $CuAl_2$ plates and β' (Mg_2Si) needles [14,15].

When the temperature and the aging time increase the density of GP zones will also increase. Hence, the degree of irregularity in the lattices will cause an increase in the mechanical properties of the Al-alloy[16]. Further increase in the aging time to 6 h at 175°C decreases the hardness of the alloy as 76kg\mm^2 (water quenching) and 59 kg\mm^2 (oil quenching). This could be due to coalescence of the precipitates into larger particles which will cause fewer obstacles to the movement of dislocation, and also due to annealing out of the defects. Generally, from figure (6) it can be noted that, the curve of hardness for the samples which are quenching in water is higher than the curve of samples which are quenching in oil as a result of high cooling rate that can be obtained from water comparing with oil.

Tensile Curves

Stress–strain curves for all aging conditions are presented in Figures(7 and 8). From the figures it can be noted that, the formation of solute clusters and the subsequent precipitation leads to higher yield and flow stress.

The yield stress and ultimate tensile strength increase rapidly with aging time and the overall shape of the stress–strain curve changes. In over-aged conditions, the flow stress decreases, as expected. However, the behavior changes dramatically at peak age, when the microstructure is dominated by small (nanoscale) β (Mg_2Si) precipitates [15]. When the Samples aged longer, the strain hardening rate decreases significantly with increasing aging time. This is attributed to the formation of a dense population of β (Mg_2Si) precipitates from Mg and Si co-clusters [17]. Also the reduced in strain hardening observed for the β (Mg_2Si) dominated microstructure as a result of the particles loose coherency upon continued annealing. The variation of the yield strength and ultimate tensile strength (UTS) with aging time is shown in figures (9 and 10). The values of yield strength and ultimate tensile strength (UTS) of the 6061 Al-alloy respectively, after solutionizing and aging for 2 h are (235MPa) and (265 MPa) for water quenching and (189MPa) and (235MPa) for oil quenching but with increasing the aging time at 175°C the strength of the samples will increase. The alloy achieves its maximum yield strength and ultimate tensile strength (UTS) respectively at 175°C when aged for 4 h as (274MPa) and (286MPa) for water quenching and (205MPa) and (243MPa) for oil quenching. An increase in strength could be explained by diffusion assisted mechanism, and also by hindrance of dislocation by impurity atoms, i.e. foreign particle of second phase. The results when using oil quenching (the yield point and ultimate tensile strength) is smaller from the results when using oil quenching solution and this is due to both reduction of strain hardening rate and to the reduction of the strain to failure. The formation of Mg and Si co-clusters takes place initially. These contribute marginally to increasing the yield stress, peak-aging is associated with a dense population of β needle shaped precipitates aligned in the <0 01> Al crystal directions, which appear to be optimal barriers for dislocations [18]. F. Ozturk et al. showed that as the aging time increases, the yield strength and ultimate tensile strength increase while the strain hardening coefficient decreases. The variation of the strength coefficient is not significant. The reduction of the strain hardening coefficient is associated with the transition from precipitate shearing to no precipitate shearing as aging time increases[6]. The values of yield strength and ultimate tensile strength decrease respectively with increasing aging time to 6h as (258MPa) and (264MPa) for water quenching and (199MPa) and (235MPa) for oil quenching, this is due to both reduced strain hardening rate and also annealing out of the defects. The elongation follows an inverse relation with the strength, as expected [1].

The Figure (11) shows the elongation as a function of artificial aging time for the samples. The elongation of the 6061 Al-alloy after solutionizing and aging for 2 h is (15.7) for oil quenching and (11.2) for water quenching but with increasing the aging time at 175°C to 4 h the elongation of the samples will drop to (12.6) for oil quenching and (9.2) for water quenching as a result of precipitation of $CuAl_2$ and Mg_2Si phase particles. The drop in elongation could be explained by diffusion assisted mechanism and also by hindrance of dislocation by impurity atoms (foreign particle of second phase)[6]. From Figure (11) can be noted rising in the value of elongation when the aging time increases in to 6 h at 175°C as (15.9) for oil quenching and (10.6) for water quenching. This could be due to coalescence of the precipitates into larger particles which will cause fewer obstacles to the movement of dislocation, and also due to annealing out of the defects. Generally, the curve of elongation for the samples which are quenching in oil is higher than the curve of samples which are quenching in water as a result of high cooling rate that can be obtained from water comparing with oil.

Conclusions

In this study, stander 6061 Al-alloy was solution heat treated, quenching in water and oil and aged in (2, 4, and 6) h. The effect of different solution of quenching and different aging time on the microstructure and mechanical properties was determined. The following conclusions are obtained:

1. The strengthening effect of 6061 Al-alloy could be explained as a result of interference with the motion of dislocation due to the formation of precipitates and to the presence of foreign particle of any phases.
2. The hardness of 6061 Al-alloy will increase with increasing the aging time at 175°C. Further increase in aging time decreases the hardness of the alloy. This could be due to coalescence of the precipitates into larger particles which will cause fewer obstacles to the movement of dislocation and hence the hardness starts to decrease.
3. The stress–strain curve changes increase rapidly with aging time. When the samples were aged longer stress–strain curve decreases significantly. The yield stress and ultimate tensile strength (UTS) were increasing with increase the aging time from 2h to 4 h.
4. The strength and hardness of samples which are quenching in water is higher than the strength and hardness of samples which are quenching in oil.
5. The elongation of samples follows an inverse relation with the strength and hardness as a result of the changing of the structure when the quenching media is changed.

Table (1): Chemical Composition of 6061 aluminum alloy.

Element	**Mg**	**Si**	**Cu**	**Fe**	**Mn**	**Cr**	**Zn**	**Ti**	**Al**
Wt%	0.82	0.73	0.29	0.36	0.03	0.019	0.14	0.05	Bal.

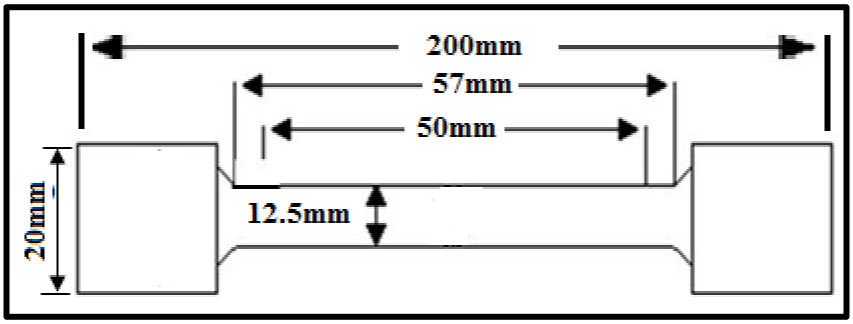


Figure. (1). Sample stander depended ASTM- E8 for tensile test.

Table (2): Quenching media physical properties.

Quenching Media	Temp (^{0}c)	Specific Gravity	Specific Heat Capacity (JKg-10k)	Density (Kg/m^3)	Viscosity Ns/m^2
water	25	1.035	4188	1000	0.9×10^{-3}
Engine oil [SAE 20 W-50	25	0.874	1890	890	45×10^{-3}

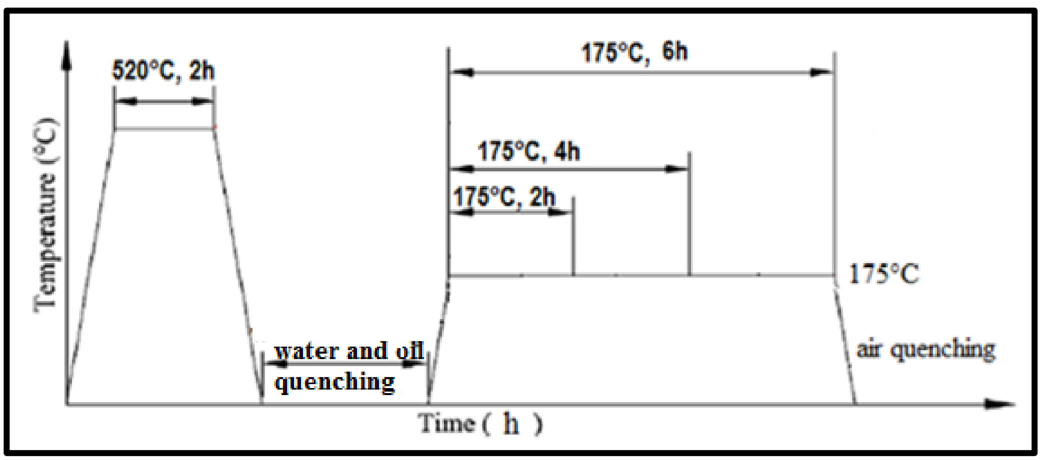
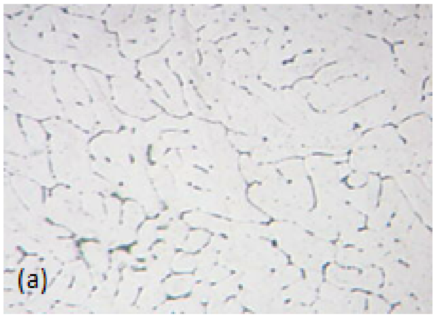
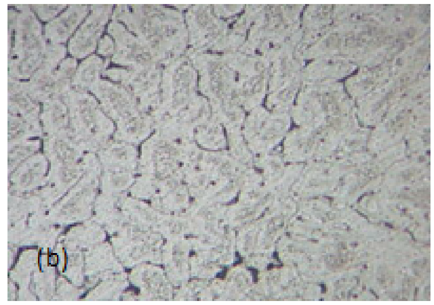


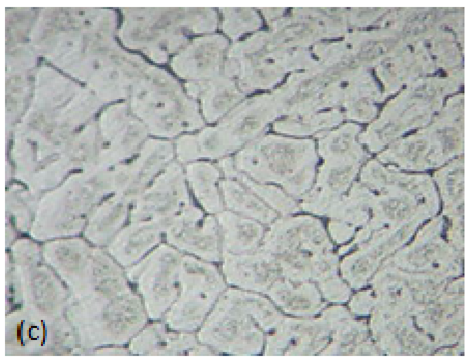
Figure.(2). Aging process diagram for 6061 Al alloy, with all aging conditions.



(a): Aluminum 6061 quenched in water and aged for 2h at 175° C. Precipitates of second phase in Al-matrix(mag x 250)

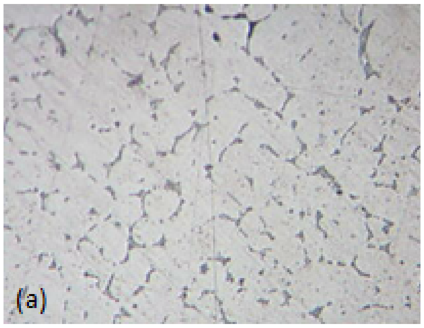


(b): Aluminum 6061 quenched in water and aged for 4 h at 175° C. increasing in Precipitates of second phase in Al-matrix(mag x 250)

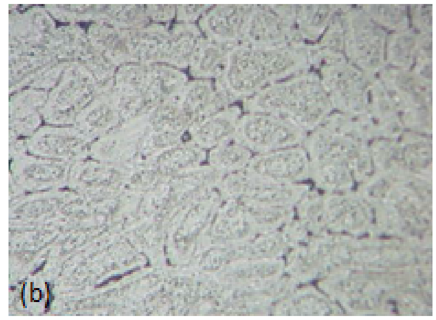


(c) :Aluminum 6061 quenched in water and aged for 6 h at 175° C. coalescence of precipitates of the second phases in Al-matrix(mag x 250)

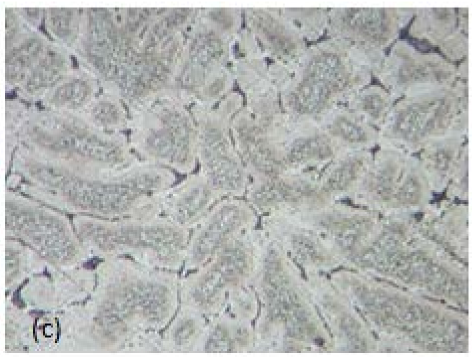
Figure. (3). Microstructure by optical microscopy for 6061 Al alloy, 250X, solution heat treated at 520°C for 2 h, water quenching and aging time (a) 2h(b) 4h (c) 6h .



(a):Aluminum 6061 quenched in oil and aged for 2 h at 175°C. pre -cipitates of the second phases in Al-matrix(mag x 250)



(b):Aluminum 6061 quenched in oil and aged for 4 h at 175°C. increasing in precipitates of the second phas- es in Al-matrix (mag x 250)



(c):Aluminum 6061 quenched in oil and aged for 6 h at 175°C. coalescen- ce of precipitates of the second phases in Al-matrix (mag x 250)

Figure. (4). Microstructure by optical microscopy for 6061 Al alloy,250X, solution heat treated at 520°C for 2h, oil quenching and aging time a) 2h b) 4h c) 6h .

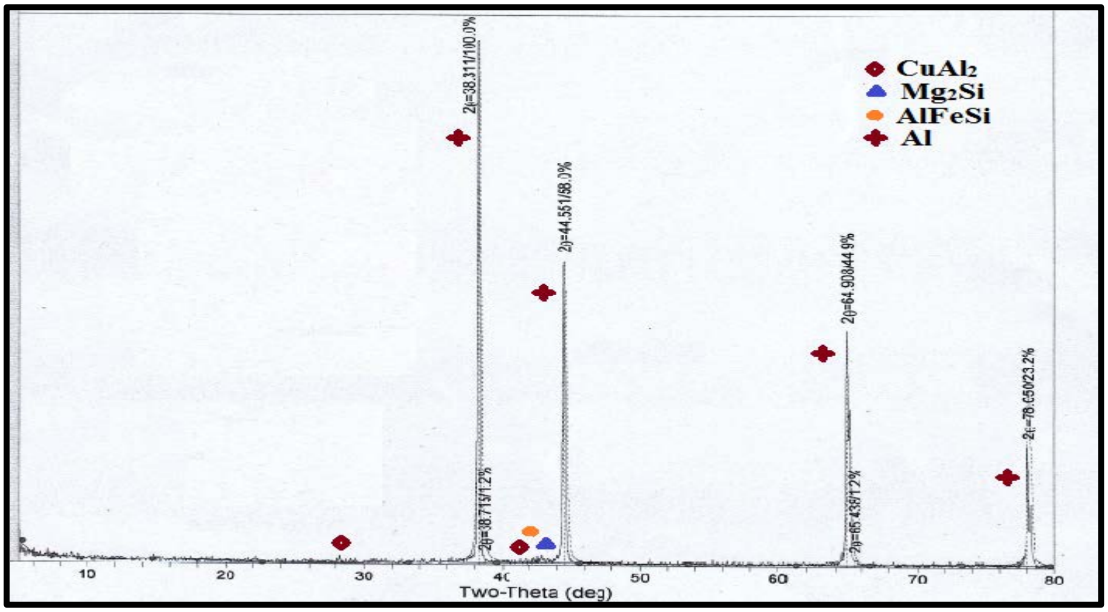


Figure. (5). XRD patterns of precipitates extracted from the alloy 6061 Al-alloy. Solution heat treated at 520°C for 2h, water quenching and aging time 4h

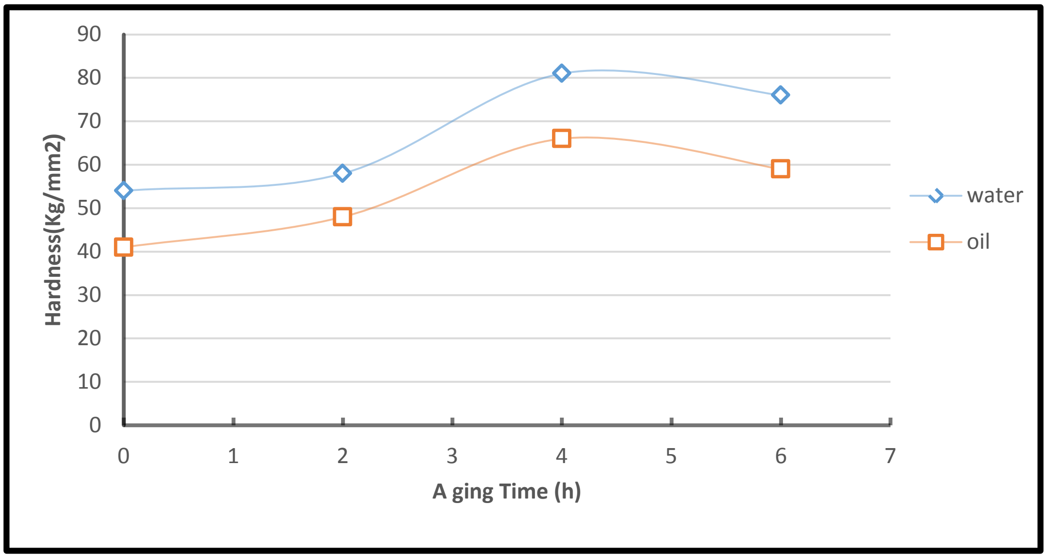


Figure. (6). Hardness values of 6061 Al alloy , solution heat treated at 520°C for 2h and quenching in water and oil with different aging.

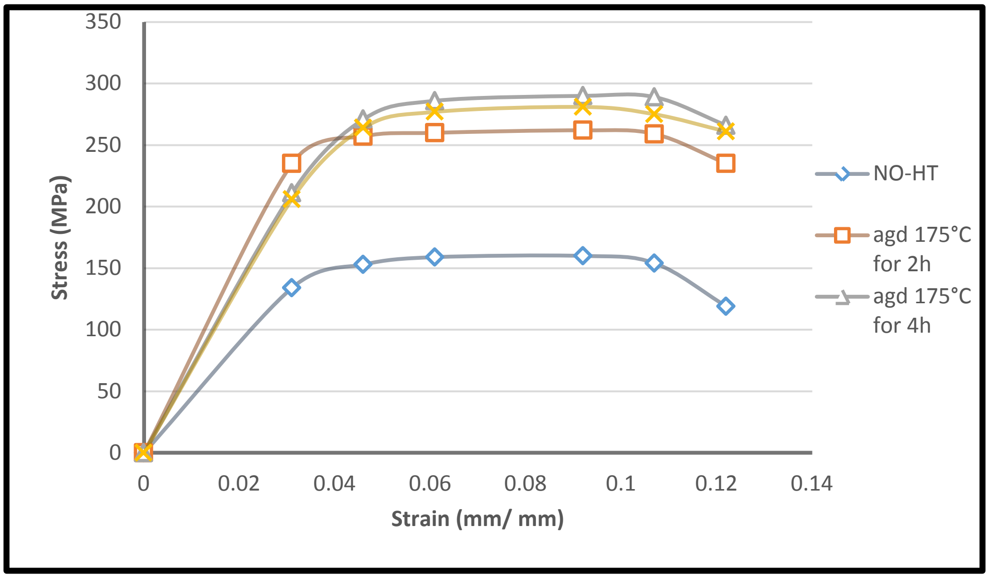


Figure. (7). True stress vs. true strain curves for 6061 Al alloy , solution heat treated at 520°C for 2h and quenching in water.

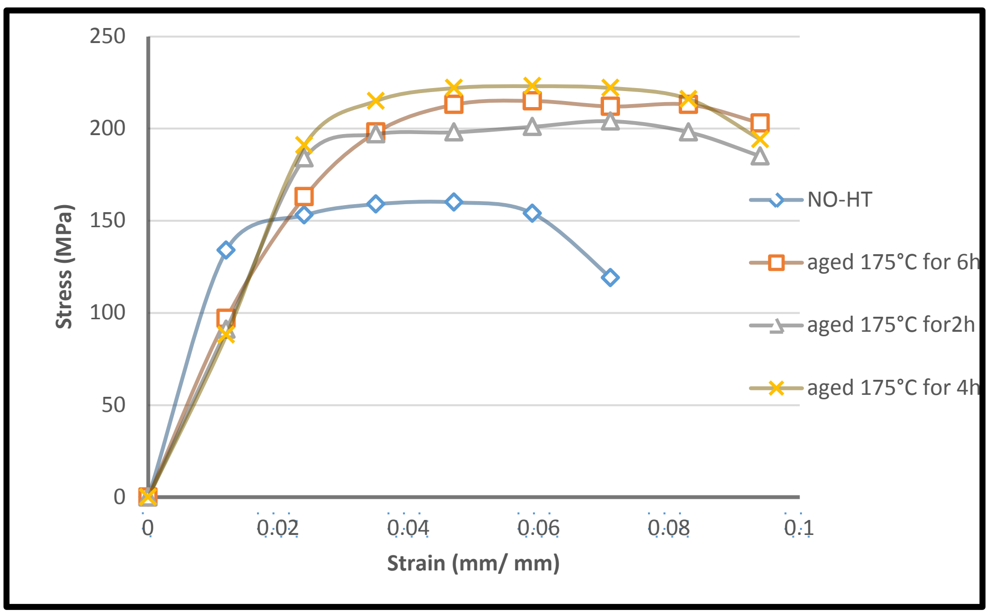


Figure. (8). True stress vs. true strain curves for 6061 Al alloy , solution heat treated at 520°C for 2h and quenching in oil.

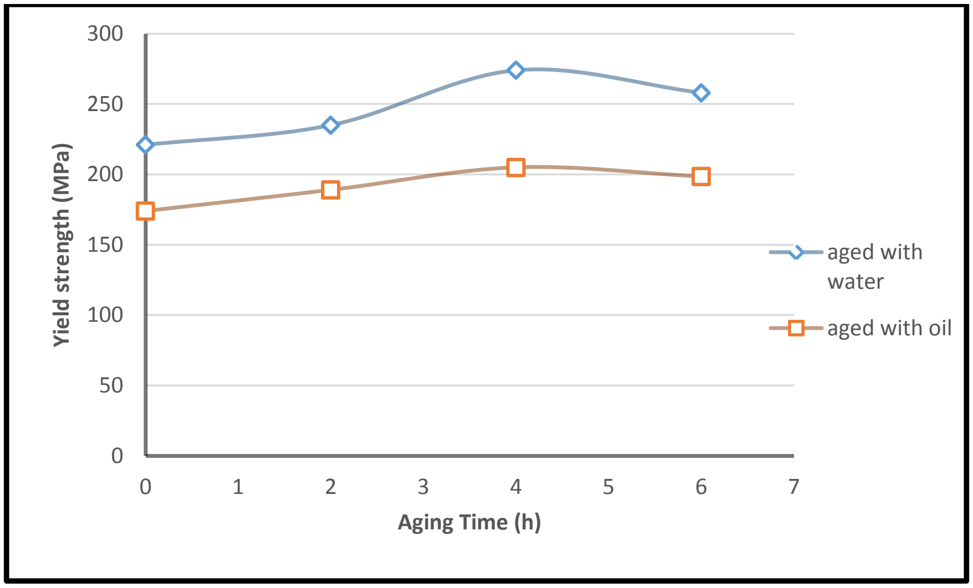


Figure. (9). Yield strengths vs. various aging time curves for 6061 Al alloy, solution heat treated at 520°C, 2h with water and oil quenching.

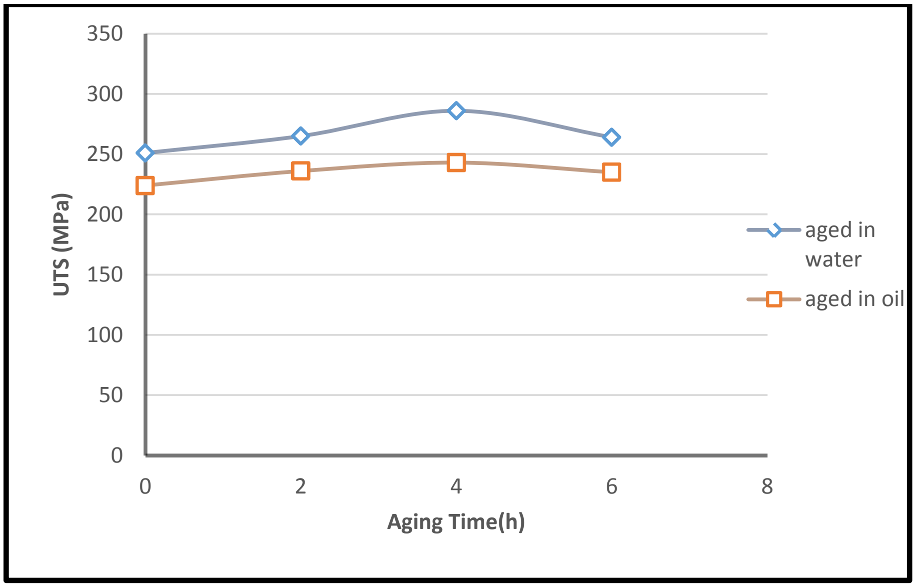


Figure. (10). Ultimate tensile strengths for various aging time curves for 6061 Al alloy, solution heat treated at 520°C, 2h with water and oil quenching.

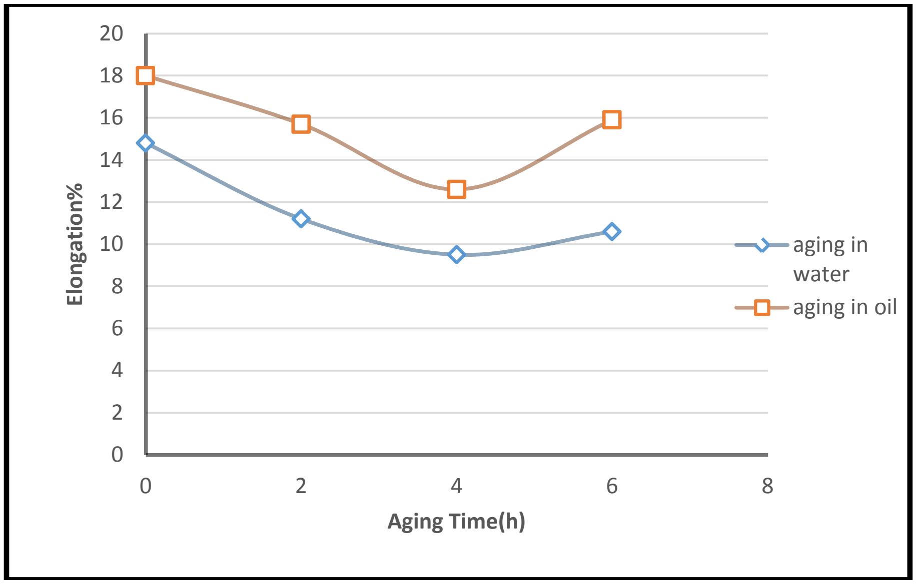


Figure. (11). Elongation values of 6061 Al alloy , solution heat treated at 520°C for 2h and different aging time in water and oil quenching.

References

[1] El-Menshawy K., Abdel-Wahab A., Mohammed E., Hafez A.," Effect Of Aging Time At Low Aging Temperatures On The Corrosion Of Aluminum Alloy 6061", Corrosion Science 54 (2012) 167–173.

[2] Maisonnette D., Suery M., Nelias D., Chaudet P., Epicier T.,"Effects Of Heat Treatments On The Microstructure And Mechanical Properties Of A 6061 Aluminium Alloy", Materials Science And Engineering A 528 (2011) 2718–2724.

[3] Ozturk F., Sisman A., Toros S., Kilic S., Picu R.C., "Influence Of Aging Treatment On Mechanical Properties Of 6061 Aluminum Alloy", Materials And Design 31 (2010) 972–975.

[4] Mostafa M.,Bahman M. ,"Influence Of Sequence Of Cold Working And Aging Treatment On Mechanical Behaviour Of 6061 Aluminum Alloy", Trans. Nonferrous Met. Soc. China 22(2012) 2072−2079.

[5] Enaam O.,"Effect of Quenching Media onWear Resistance of AISI 52100 Bearing Steel Alloy".Eng. &Tech. Journal, Vol.31, Part (A), No.14, 2013.

[6] Demir H., Gunduz S." The effects of aging on machinability of 6061 aluminum alloy". Mater Des 2009;30:1480–3.

[7] Abdulwahab M., Madugu I. A., Asuke F., Fayomi O.S.I., and Ayeni F. A., " Effect of thermal ageing treatment on the mechanical properties of antimony-modified A356.0-type Al-Si-Mg alloy", J. Mater. Environ. Sci. 4 (1) (2013) 87-92, ISSN : 2028-2508.

[8] Doward R., Bouvier C. "A rationalization of factors affecting strength, ductility and toughness of AA6061-type Al–Mg–Si–(Cu) alloys". Mater Sci Eng A 1998;254:33–44.

[9] Kim H., Cho S., Kang C. "Evaluation of microstructure and mechanical properties by using nano/micro-indentation and nanoscratch during aging treatment of rheo-forged Al 6061 alloy". Mater Sci Eng A 2008;485: 272–81.

[10] Abbas S.,"Effect of Quenching Media on the Mechanical Properties and Abrasive Wear Resistance of (34Cr4) Steel Blade with Soil Texture Used in Agricultural Equipments". Eng. & Tech. Journal , Vol.32, Part (A), No.9, 2014.

[11] Ozturk F., Esener E., Toros S., Catalin R., "Effects Of Aging Parameters On Formability Of 6061-O Alloy" Materials And Design 31 (2010) 4847–4852.

[12] Edwards G., Stiller K., Dunlop G., Couper M. "The precipitation sequence in Al– Mg–Si alloys". Acta Mater 1998;46:3893–904.

[13] Murayama M., Hono K., Miao W., Laughlin D. "The effect of Cu Additions on the precipitation kinetics in an Al–Mg–Si alloy with excess Si".
Metal Mater Trans A 2001;32:239–46.

[14] Tash M., Samuel F., Mucciardi F., Doty H., Valtierra S. "Effect of metallurgical parameters on the machinability of heat-treated 356 and 319 aluminum alloys".
Mater Eng A 2006;434:207–17.

[15] Rafig A., Hussein A., Khamis R. "Influence of aging parameters on the mechanical properties of 6063 aluminium alloy". J Mater Process Technol 2000;102:234–40.

[16] Yassar S., Field P. "Transmission electron microscopy and differential scanning calorimetry studies on the precipitation sequence in an Al–Mg–Si alloy: AA6022".
J Mater Res 2005;20:2705–11.

[17] Marioara C., Nordmark H., Andersen S., Holmestad R. "Post-b00 phases and their influence on microstructure ad hardness in 6xxx Al–Mg–Si alloys". J Mater Sci 2006;41:471–8.

[18] Edwards G., Stiller K., Dunlop G., Couper M. "The precipitation sequence in Al– Mg–Si alloys". Acta Mater 1998;46:3893–904.