# The Effect of Rolling and Heat Treatment on Mechanical Behavior of 6061 Aluminum Alloy

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**Abstract**

In this study, the influence of both heat treatment and cold working (rolling) on the tensile properties and hardness of 6061 aluminum alloy sheets was investigated. The solution heat treatment is first performed at about 520°C 1 hr followed by rolling to(40% and 60%). Artificial aging is obtained by heating to about 180 °C for 1/2hr and 2 hr. The experimental work has revealed that when two strengthening mechanism (cold work and aging) are combined, the values of the mechanical properties are come up. Increasing the aging time from ½ hr to 2hr with redaction in area was causing increase in the values of the strength and hardness and dropping the elongation. In the other hand, increasing the redaction in area from (40%) to (60%) with aging was rising the value of the strength and hardness and dropping the elongation. The changes in mechanical properties were discussed as a result of increasing the dislocation density(result of rolling) and formation of precipitation(effect of aging) which are interface with the motion of dislocation and causes hindering of dislocation.

**Key words:** 6061 Aluminum Alloy, Age Hardening, Rolling, Mechanical Properties.

## تأثير الدرفلة والمعاملة الحرارية على السلوك الميكانيكي لسبائك المنيوم 6061

**الخلاصة**

في هذاالبحث تم دراسة تأثير كلاً من المعاملة الحرارية و التشكيل على البارد (الدرفله) على الخواص الميكانيكية والصلادة لصفائح من سبيكة المنيوم 6061. تم اجراء معاملة حرارية للصفائح عند 520 م° لمدة ساعة واتبعت المعاملة بالدرفلة بمقدار (40% و60%) بعدها يتم اجراء التعتيق عند درجة حرارة 180 م° لمدة (1/2 و2) ساعة .تبين نتائج الجانب العملي التالي,ان جمع اليتين من اليات التقوية تزيد من الخواص الميكانيكية لسبيكة المنيوم 6061. ان رفع زمن التعتيق من نصف ساعة الى ساعتين مع اختزال المساحة (الدرفلة) يؤدي الى رفع قيم المقاومة والصلادة وخفض المطيلية , ومن ناحية اخرى, فأن زيادة كمية الاختزال من(40%) الى (60%) مع التعتيق يرفع من قيم المقاومة و الصلادة و يخفض المطيلية . ان التغيرات في الخواص الميكانيكية هو نتيجة لزيادة كثافة الانخلاعات(بسبب الدرفلة) و زيادة الترسيب (بسبب التعتيق)و الذي يتداخل مع الانخلاعات مما يسبب اعاقة لحركتها .

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## INTRODUCTION

In recent years, aluminum alloys have attracted attention of many researchers, engineers and designers as promising structural materials for automotive industry or aerospace applications. Especially,6xxx aluminum alloys have been studied extensively because of their benefits such as medium strength, formability, weldability, corrosion resistance, and low cost, comparing to other aluminum alloys [1,2]. Mg and Si are the major solutes; they increase the strength of the alloy by precipitation hardening, there has been considerable industrial interest in these alloys because two-thirds of all extruded products are made of aluminum, and 90% of those are made of 6XXX series alloys [3]. Work hardening and precipitation hardening are common strengthening mechanisms of 6xxx series of aluminum alloys [4]. When cold working is combined with age treatment, two main microstructural processes are competing with each other[5]. The solution heat treatment is first performed at about 500 °C to obtain the supersaturated α a solid solution, artificial aging is obtained by subsequently heating to about 200 °C for various amounts of time and leads to precipitation of various phases, the hardness and strength are determined by the precipitate type, density, and size [6].Work hardening as a result of increase of dislocation density over cold working and dislocation pinning by precipitates formed during age treatment increases strength of material and reduces its elongation[5]. The effect of various designated heat treatments and cold working on mechanical behavior of Al−Mg−Si alloys have been investigated in some previous studies [7-10]. Chang et al. investigated the effect of natural pre-ageing on artificial aged Al-Mg–Si alloy. They revealed that natural pre-ageing has a positive effect in artificial aged Al-Mg–Si alloy and the natural ageing increases volume fraction of fine precipitates and improves the mechanical properties significantly [7]. de Haas et al. discussed the Preferential precipitation at grain boundaries, the chemistry and crystallography of these precipitates. The presence of grain boundary precipitates in particular in Si-rich alloys promotes intergranular fracture and reduced overall ductility [8]. Halil D. and Süleyman G. investigated the effect of artificial aging on the machinability of 6061 Al-alloy as-received, solution heat treated (SHT) and solution heat treated and then aged (SHTA) conditions. Their results revealed that different aging times at 180 °C and cutting speed significantly affected on the machined surface roughness values [9].KIM et al investigated the mechanical and tribological properties of rheo-formed wrought AA6061 alloy. Peak hardness and surface roughness were determined after a 530 °C solution heat treatment for 10 hr. Their results revealed that Surface roughness increases with the aging time [10].

In the present investigation, the mechanical properties of 6061Al-alloy subjected to solution heat treatment and aging to various degrees with and without cold work (rolling)are investigated and discussed in relation to the microstructural changes during heat treatment and rolling.

## Experimental

In the present study, 6061Al-alloy sheets with 5mm in thickness were used. The chemical composition of the materials was determined by spectrometry which is listed in Table 1.

**Table (1). Chemical composition of 6061Al-alloy alloy (mass fraction %)**

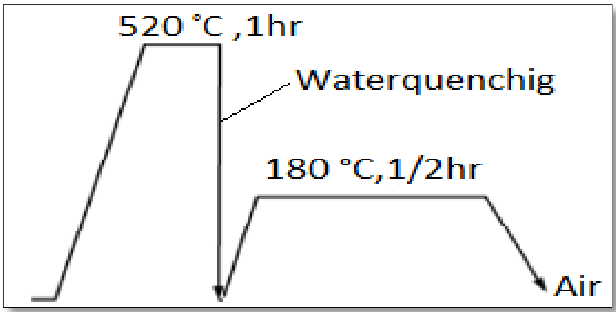
| Mg | Si | Cu | Fe | Mn | Cr | Zn | Ti | Al |
|---|---|---|---|---|---|---|---|---|
| 0.90 | 0.41 | 0.16 | 0.26. | 0.07 | 0.04. | 0.01 | 0.01 | Bal. |

In order to study the influence of various sequences of cold working and age hardening on mechanical properties of 6061Al-alloy sheets, different series of thermal mechanical treatments were utilized as illustrated in Fig.1. A resistance furnace with atmospheric environment was utilized for heat treatment. Cold working (CW) was conducted by a laboratory rolling mill to the reduction (40% and 60%) in area. Some strips were cut from 6061Al-alloy sheets along rolling direction. All samples were solutionized at 520°C for 1 hr and then quenched immediately in water. Fig.1(a) shows that, the solution heat treatment was carried out at 520°C for 1 hr followed by aging at 180 °C for 0.5 hr . Fig.1(b) Cold working (CW) was conducted by a laboratory rolling mill to reduction of 40% in area after solution heat treatment than aging at 180 °C for 0.5 hr. In fig.1(c) the sample have the same sequences of heat treatment and Cold working as Fig.1(b) but the reduction in area was to 60%. Fig.1(d) have the same sequences of heat treatment and redaction in area as Fig.1(b) but the time of aging was 2 hr. Fig.1(f) the sample have the same sequences of heat treatment , Cold working and aging for 2hr as Fig.1(d) but the reduction in area was to 60%. The hardness was examined for the polished samples surfaces using Vickers Hardness Testing machines with 9.8 N load. The vickers hardness was measured on the polished samples using diamond cone indentor and the hardness values reported here represent the average of at least three measurements. The general equations applied for determined of Vickers Hardness Testing is [11]:

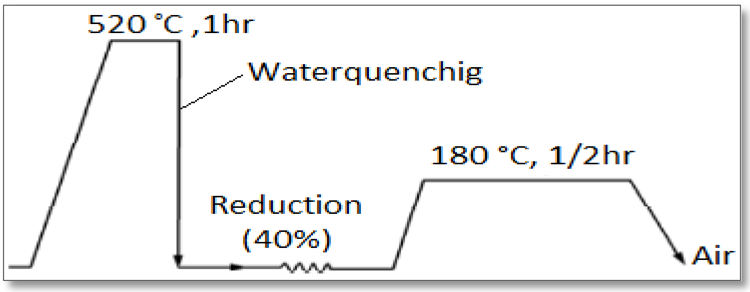
$$H.V = 1.8544 \times [P/(d_1+d_2/2)^2] \quad \text{......(1)}$$

Where:
H.V: Vickers Hardness.
P : Applied load kg.
d : Sample diameter (mm).

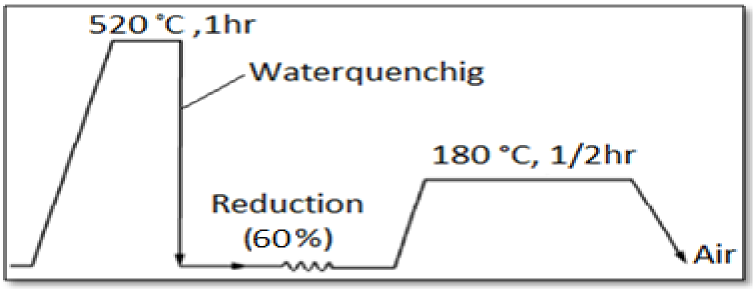
The hardness samples were cut into 20 x 20 mm cylindrical pieces then successively ground using 320, 500, and 1000 grade emery papers, were polished according to standard metallographic techniques, degreased in Alcohol and dried. Tensile test specimens were cut from the thermal mechanically treated strips. The long axis of the test specimen was parallel to the rolling direction .Tensile test specimens were then prepared according to ASTM-E8 specifications as shown in figure 2 . Tensile tests were performed with a crosshead speed of 5 mm/min. Stress—strain curves were then analyzed; next, yield, ultimate tensile strengths and elongation of samples were compared. Meanwhile, micro-hardness of samples was measured using a Vickers hardness indenter under 9.8 N load. The hardness values reported here represent the average of at least three measurements.



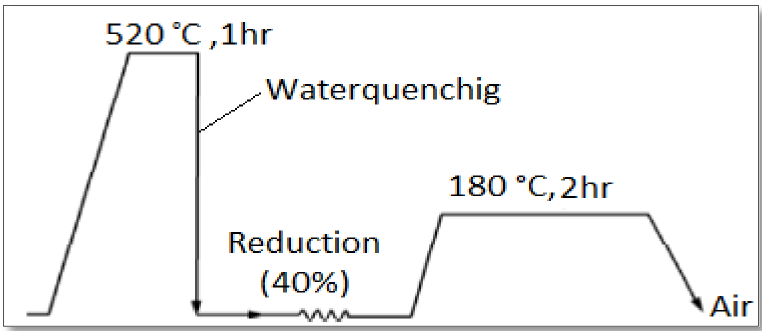

**(a) Solution heat treatment at 520 $^{o}$C /1 hr followed by artificial aging for 1/2hr.**



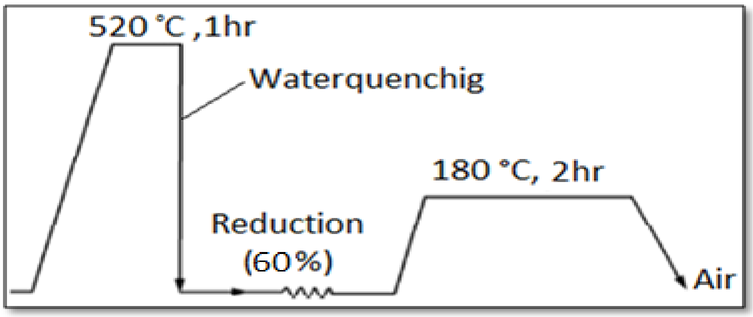

**(b) Solution heat treatment at 520 $^{o}$C /1 hr followed by rolling to (40%) then artificial aging for 1/2hr.**




**(c) Solution heat treatment at 520 $^{o}$C /1 hr followed by rolling to (60%) then artificial aging for 1/2hr.**



**(d) Solution heat treatment at 520 °C /1 hr followed by rolling to (40%) then artificial aging for 2hr.**




**(f) Solution heat treatment at 520 °C /1 hr followed by rolling to (60%) then artificial aging for 2hr.**

**Figure(1) Different series of thermal-mechanical treatments for 6061 Al alloy: (a) , (b) ,(c) ,(d) and (f).**

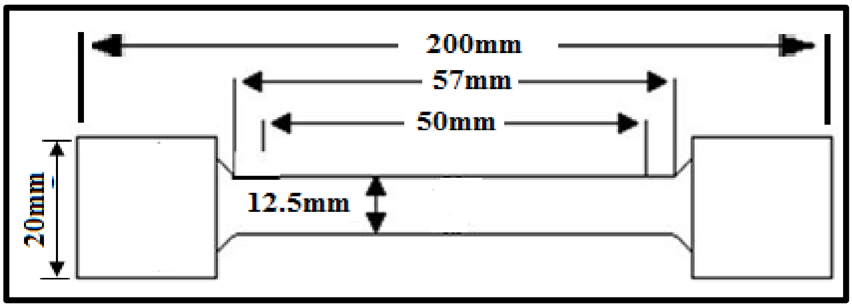



**Figure (2). Sample stander depended ASTM- E8 for tensile test.**

## Results and discussion

Employing combination of age hardening and cold rolling are important from two different points of view in the manufacturing processes. The first one is to form the material to the proper shape first and then aged. In this case the formability should be high enough before heat treatment. The second point is to age the material first in order to get high resistance to thinning and then formed. If the material has high strength and excellent ductility, there is no limitation in sequence of manufacturing processes [12].

## Stress-Strain Curves

Stress–strain curves for all rolling and aging conditions are presented in Fig. 3. It can be noted that when the values of aging time and deformation increase from ½ h to 2 h and 40% to 60% respectively, the stress–strain curves are coming up. The formation of solute clusters and the subsequent precipitation leads to higher yield and flow stress [11].The strengthening effect of 6061 Al-alloy could also be explained as a result of interference with the motion of dislocation due to the presence of foreign particle of any phases [9]. Further increase in the aging time to 2h at 180 °C causes increasing in precipitation and interference with the motion of dislocation which increase the overall shape of the stress–strain curve. From fig.3 it can be noted that increasing the redaction in area from (40% to 60%) lead to rising of stress-strain curves. Cold working increases the dislocation density in the structure of material which in turn rises the yield and flow stress of alloy. When the cold rolled strips were subject to age treatment, additional strengthening mechanism occurs as a result of that, the shape of the stress–strain curves come up.

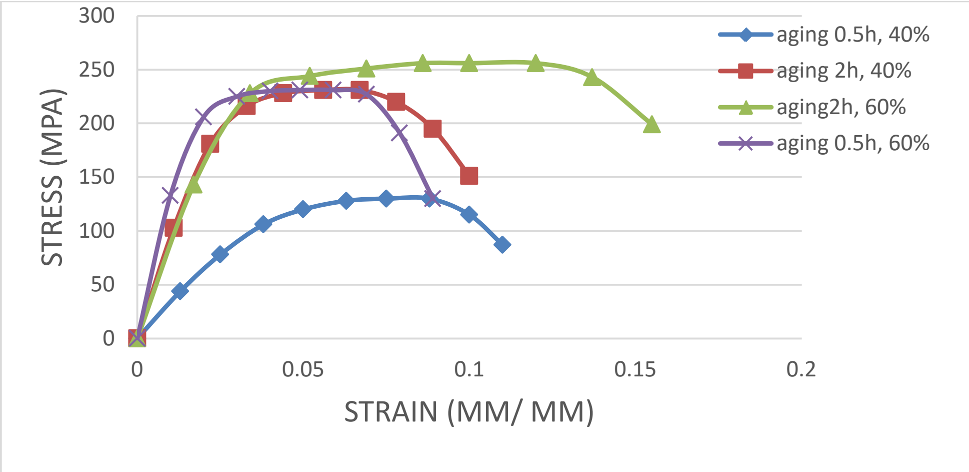
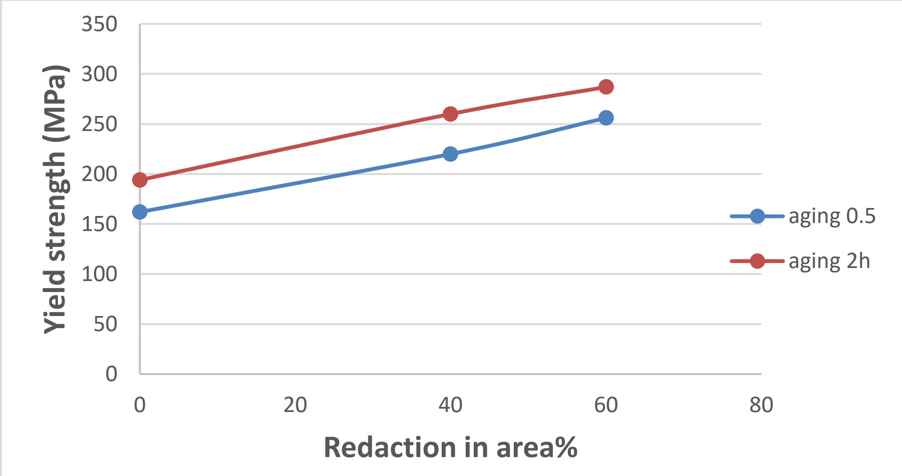



**Figure (3). True stress vs. true strain curves for 6061 Al alloy , solution heat treated at 520°C for 1hr with redaction in area (40%and 60%) and aging for (1/2hr and 2 hr).**

**The yield and ultimate strengths**

The influence of cold working and heat treatment on yield and ultimate strengths respectively are shown in Figs. 4 and 5. As Figs. 4 and 5 illustrated, by increasing the amount of reduction in area from 40% to 60%, the yield and ultimate strengths of materials come up. During cold working, dislocation density in the structure of material increases which result rising of yield strength and ultimate tensile strength. There are strong interactions between the solute atoms and defects in aluminum alloys that result in structural instabilities, variation in solute profiles and changes in solute diffusion rates. Mobile dislocations are pinned by enhanced solute diffusion during tensile straining[13].Plastic deformation not only increases the mobility of solute atoms in aluminum alloys but also cause clustering at dislocations and these clusters act as nucleation sites for subsequent strengthening precipitates at temperatures well below the conventional aging temperatures [14]. While the cold rolled strips are subjected to age treatment, further strengthening could occur, which increases the strength of the material.

The strengthening effect of 6061 Al-alloy could also be explained as a result of interference with the motion of dislocation due to the presence of foreign particle of any other phase[9]. Rafiq et al. [15] showed that as the aging time increases, 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[9].from the results it can be observe that aging at 180 °C for 1/2hr leads to higher values of the yield and ultimate tensile strengths. 6061Al-alloy achieves its maximum yield and ultimate tensile strengths at 180 °C when aged for 2 h. An increase in yield and ultimate tensile strengths could be explained by diffusion assisted mechanism, and also by hindrance of dislocation by impurity atoms, i.e. foreign particle of second phases.




**Figure(4). Yield strengths vs. redaction in area(40% and 60%) curves for 6061 Al alloy, solution heat treated at 520°C for 1hr and aging for ½ hr and 2 hr.**

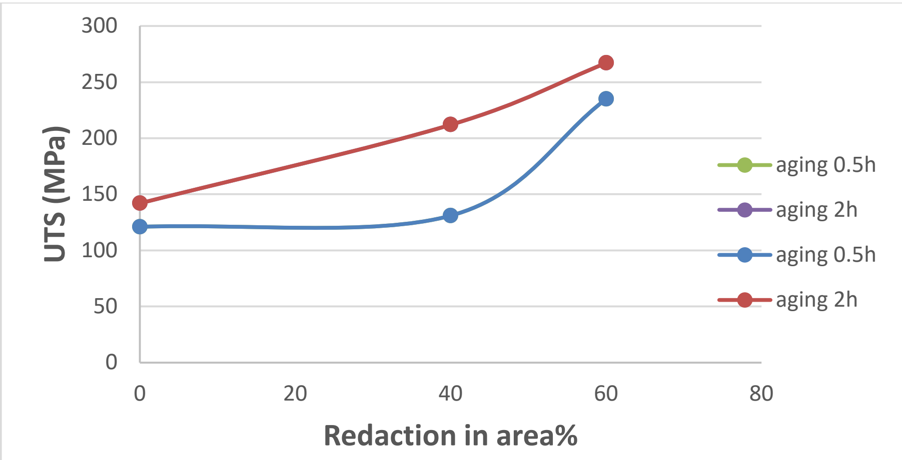
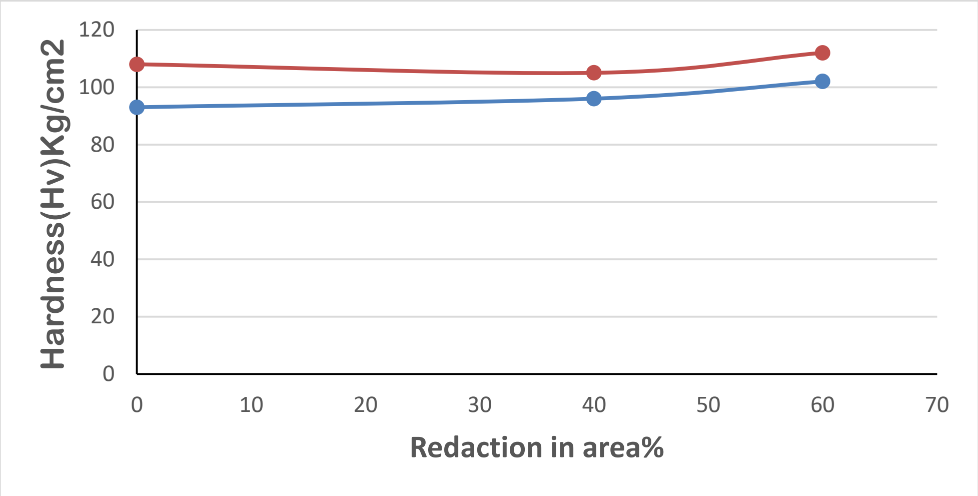



**Figure (5). Ultimate tensile strengths vs. redaction in area(40% and 60%) curves for 6061 Al alloy, solution heat treated at 520°C for 1hr and aging for ½ hr and 2 hr.**

**Hardness**

Fig. 6 shows the effect of rolling and aging time on hardness of 6061 aluminum alloy. The hardness of the 6061 Al-alloy, immediately after water quenching and (1/2hr) aging is as low as (93) HV, but the value of hardness is increasing with applying cold working and artificial aging. The value of hardness after applying (40%) cold working and aging for (1/2h) is equal to (96)HV, the dislocation density in the structure of material increases during cold working, which cause increasing in hardness. the value of hardness increases as the amount of deformation increases[16]. With increasing the aging time to (2hr) at the same redaction in area (40%), the hardness will come up to (105) HV because the aging treatment lead to further strengthening as a result of increasing the density of GP zones[15] . Hence, the degree of irregularity in the lattices will cause an increase in the mechanical properties of the Al-alloy. Increase of amount of reduction in area to (60%) with aging to (1/2h) rising the value of hardness to (102) HV. During cold working, the dislocation density in the structure of material increases, which results in rise of yield strength, ultimate tensile strength and hardness. Meanwhile, heavy strain provides more nucleation sites for precipitation and gives rise in the strength and hardness [5]. With increasing the aging time to (2hr) at the same redaction in area (60%), the hardness will come up to (112) HV because the aging treatment lead to further strengthening as a result of increasing the density of GP zones and that causing interference with the motion of dislocation due to the presence of foreign particle of GP zones.




**Figure(6). Hardness vs. redaction in area(40% and 60%) curves for 6061 Al alloy, solution heat treated at 520°C for 1hr and aging for ½ hr and 2 hr.**

**Elongation**

The figure (7) shows the elongation as a function of artificial aging time with different redaction in area for the samples. The elongation of the 6061 Al-alloy after solutionizing and aging at 180 °C for 1/2 h is (15.5) .with applying rolling to (40%) the value of elongation will drop down as (11.5). The drop in elongation could be explained as a result of increasing the dislocation density in the structure of material during cold working [5]. Meanwhile, heavy strain provides more nucleation sites for precipitation of 6061 Al-alloy. The aging at 180 °C for 2 hr leads to drop the elongation to (10) and that could be explained by diffusion assisted mechanism and also by hindrance of dislocation by impurity atoms (foreign particle of second phase) [9]. Increase of amount of reduction in area to (60%) decreases elongation as (9) due to increase in dislocation density, which makes difficulty for flow of material. The aging at 180 °C for 2 hr with same amount of reduction in area (60%) leads to decrease the elongation to (7.5) as a result to increase the density of GP zones which causes pinning of dislocation by precipitates formed during age treatment [13].

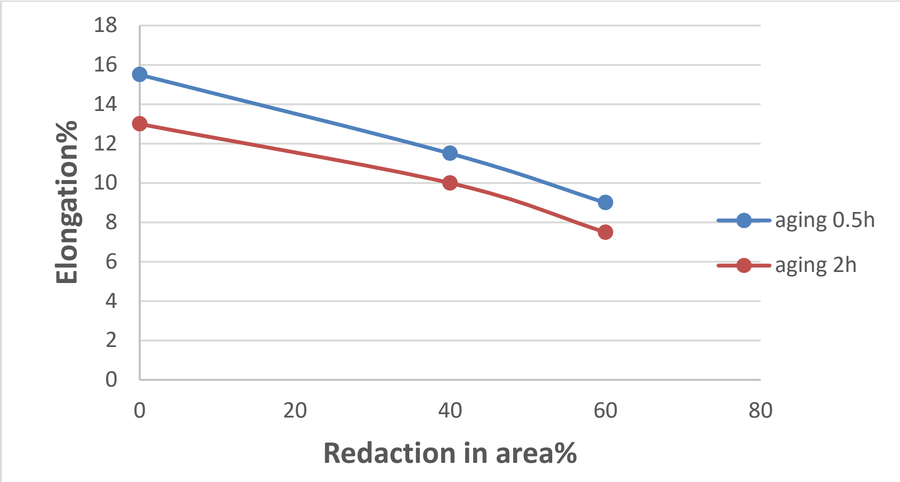



**Figure (7). Elongation vs. redaction in area(40% and 60%) curves for 6061 Al alloy, solution heat treated at 520°C for 1hr and aging for ½ hr and 2 hr.**

**Conclusions:**

The conclusions derived from this study can be given as follows:

1. Employing combination of age hardening and cold rolling are important for the strengthen of 6061 Al-alloy as a result of increasing the density of dislocation and formation of precipitates which hindered the motion of dislocation.
2. The stress–strain curves increase with increasing aging time from 1/2h to 2h and redaction in area from 40% to 60% as a result of interference with the motion of dislocation due to the formation of precipitates and increasing the density of dislocation.
3. An increase in yield strength, ultimate tensile strength and hardness of 6061 Al-alloy during cold working because of the dislocation density in the structure of material increases. Meanwhile, heavy strain provides more nucleation sites for precipitation and gives rise in mechanical properties.
4. The mechanical properties increase with increasing the aging time at 180 °C which can be explained by a diffusion assisted mechanism and that causes an increase in the density of GP zones, distortion of lattice planes and hindering of dislocation movement by the impurity atoms. The strengthening effect can also be as a result of interference with the motion of dislocation, due to the formation of precipitates.
5. The value of elongation is dropping with Increasing the amount of reduction in area and rising the aging time due to increase the dislocation density and formation of precipitation and hindrance of dislocation by this precipitation which makes difficulty for flow of material.

**References**

[1] Altenpohl DG.," Aluminum: Technology, Applications, and Environment, A Profile Of A Modern Metal". Book, 6th Ed, Washington, D.C. : Aluminium Assoc. [U.A.], 1998.

[2] Troeger LP.and Starke EA. ,"Microstructural And Mechanical Characterization Of A Superplastic 6xxx Aluminum Alloy". Materials Science And Engineering A, 277: 102−113, 2000.
[3] Parson NC. and Yiu HL., "Proceedings Of Light Metals Conference", Las Vegas,February 1989, Ed. By P. G. Campbell (TMS/AIME), Warrendale, Pennslvania, United States, 1989, P. 713.
[4] Smith W F. "Structure And Properties Of Engineering Alloys".: Second Edition,Mcgraw-Hill, Inc.,New York, 1993.
[5] Mansourinejad M.and Mirzakhani B., "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 .
[6] Buha J., Lumley RN., Crosky AG.,and Hono K.," Secondary Precipitation In An Al–Mg–Si–Cu Alloy". Acta Mater;55:3015–24, 2007.
[7] Chang CST., Wieler I., Wanderka N., and Banhart J. ,"Positive effect of natural pre-ageing on precipitation hardening in Al–0.44 at% Mg–0.38 at% Si alloy", Ultramicrosc 2009;109:585–2.
[8] De Haas M., Van Scherpenzeel SM.and De Hosson JTM., "Grain Boundary Segregation and Precipitation in Al Alloy AA6061",. Mat Sci Forum 2006;519–521:467–72.
[9] Demir H.and Gunduz S.," The Effects Of Aging On Machinability Of 6061 Aluminium Alloy",Materials And Design 30 (2009) 1480–1483, Www.Elsevier.Com.
[10] Kim HH. , Cho SH.,and Kang CG. ," 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.
[11] Ozturk F., Sisman A., Toros S., Kilic S.,and Picu RC., "Influence Of Aging Treatment On Mechanical Properties Of 6061 Aluminum Alloy", Materials And Design 31 (2010) 972–975.
[12] Mirzakhani B. and Mansourinejad M., "Tensile Properties of AA6061 in Different Designated Precipitation Hardening and Cold Working", Procedia Engineering 10 (2011) 136–140
[13] Lassance D., Schmitz, M., Delannay F. and Pardoen, T., "Linking Microstructure and High Temperature Ductility In Aluminum Alloys AA6xxx." Seminar Paper Available Online At: Www.Hallf.Kth.Se/Forskning/Ecf15/ECF-Proceedings/Lassance, (2002).
[14] Valiev R., Krashkov N. and Tsenev K., "Plastic Deformation of Alloys with Submicron-Grained Structure." Materials Science and Engineering, Vol.153, Issue 3, Pp.172-196, (1991).
[15] Rafig AS, Hussein AA, and Khamis RA. "Influence of Aging Parameters on the Mechanical Properties of 6063 Aluminium Alloy. J Mater Process Technol 2000;102:234–40.
[16] Radović Lj.and Nikačević M. , "Microstructure And Properties Of Cold Rolled And Annealed Al-Mg Alloys", Scientific Technical Review,Vol.Lviii,No.2,2008