MEEN 160

MATERIALS SELECTION IN MECHANICAL DESIGN

EXPERIMENT #5

AGE HARDENING OF ALUMINUM AND THE SELECTION OF ALUMINUM ALLOYS

by

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I. Introduction

According to Smith (2004), precipitation strengthening is to create in a heat-treated alloy a dense and fine dispersion of precipitated particles in a matrix of deformable metal. The precipitate particles act as obstacles to dislocation movement and thereby strengthen the heat-treated alloy.

Smith (2004) describes the precipitation-strengthening process in three basic steps. First, the alloy is heated to a temperature between the solvus and solidus temperatures and soaked there until a uniform solid-solution structure is produced. Next, the sample is quenched (rapidly cooled to a lower temperature, usually room temperature with water as the cooling medium). The structure of the alloy after water quenching consists of a supersaturated solid solution. Finally, aging of the solution heat-treated and quenched alloy sample is necessary so that a finely dispersed precipitate forms. That formation impedes dislocation movement during deformation by forcing the dislocations to either cut through the precipitated particles or go around them. By restricting dislocation movement during deformation, the alloy is strengthened.

The purpose of this lab was to learn about how certain aluminum alloys can be hardened by heat treatment, to learn about the microstructural changes responsible for the hardening of alloys during aging heat treatment, and o learn about the temper designations for age-hardened aluminum alloys and how they are used in the selection of alloys.

This lab demonstrated the age hardening response of 6061 aluminum by first heat-treating the aluminum samples at several different aging temperatures. Next, the hardening response of the solution treated and water quenched alloy was followed by measuring the Rockwell-E hardness and tensile properties of the alloy as functions of aging temperature and time at temperatures ranging from 200˚C and 220˚C, and for times ranging from 0.01 hours to 25.0 hours.

II. Experimental Procedure

Tensile and hardness specimens for a given temperature were first solution treated in a muffle furnace for 1.0 hour at 495˚C in air, and then quenched in water. The specimens were then tied to the ends of steel wires for aging in an oil bath, and immersed in the oil bath set at predetermined temperatures for the specific specimens exactly 30 minutes after being quenched. The individual tensile and hardness specimen pairs were then removed and water quenched after the predetermined aging times for the specific specimens had elapsed.

After water quenching each tensile and hardness specimen pair, they were tested to determine hardness, yield strength, tensile strength and percent elongation. First, each aged hardness specimen was tested for hardness with the Rockwell-E test. Next, the diameter of each tensile specimen was measured in six places along the gage length with a micrometer and gage length marks were scribed. From the gage length marks, initial gage lengths were measured from each tensile specimen. The tensile specimens were then tensile tested, which produced a load elongation curve for each tensile specimen.

From the elongation curves, the tensile load corresponding with the 0.2% yield strength and the tensile strength for each specimen was determined. The two broken pieces of each specimen were then put together and the final gage lengths were measured with a caliper.

III. Results

A. Data

Table 1. Nominal Chemical Composition of 6061 Aluminum Alloy in Weight Percent

Alloy Element				
Al	Si	Cu	Mg	Cr
Bal	0.60	0.30	1.0	0.20

Table 2. Hardness and Tensile Properties of 6061 Aluminum Alloy Aged at 200 Celsius

Aging Time (hrs)	Hardness (R_E)	Tensile Properties								
		d_0(inch)	$P_{0.2}$(lbs)	P_{ts}(lbs)	L_0 (inches)	L_f (inches)	%EL	Ao (in^2)	$\sigma_{0.2}$ (psi)	σ_{ts} (psi)
0.00	26.0	0.2566±0.0032	330±50	1,018±50	1.768±0.005	2.283±0.005	29.129±0.001	0.052±0	6384.6±0.005	19695.4±0.005
0.01	27.7	0.2568±0.0016	380±50	1,010±50	1.703±0.005	2.189±0.005	28.538±0.001	0.052±0	7340.5±0.005	19510.2±0.005
0.10	42.2	0.2566±0.0018	380±50	1,020±50	1.837±0.005	2.320±0.005	26.293±0.001	0.052±0	7351.9±0.005	19734.1±0.005
0.25	66.1	0.2500±0.0032	470±50	1,120±50	1.990±0.005	2.320±0.005	16.583±0.001	0.049±0	9579.6±0.005	22828.0±0.005
0.50	85.0	0.2508±0.0008	1,035±50	1,525±50	1.957±0.005	2.229±0.005	13.899±0.001	0.049±0	20961.2±0.005	30884.8±0.005
1.00	92.0	0.2559±0.0021	1,690±50	1,900±50	1.811±0.005	2.118±0.005	16.952±0.001	0.051±0	32875.8±0.005	36961.0±0.005
2.00	93.8	0.2537±0.0020	1,730±50	1,910±50	1.848±0.005	2.070±0.005	12.013±0.001	0.051±0	34250.9±0.005	37814.6±0.005
3.00	93.0	0.2507±0.0006	1,800±50	1,960±50	1.911±0.005	2.131±0.005	11.512±0.001	0.049±0	36483.3±0.005	39726.3±0.005
4.00	93.5	0.2500±0.0013	1,675±50	1,825±50	1.785±0.005	1.835±0.005	2.801±0.001	0.049±0	34140.1±0.005	37197.5±0.005
6.00	94.6	0.2524±0.0009	1,720±50	1,920±50	1.840±0.005	2.025±0.005	10.054±0.001	0.050±0	34393.8±0.005	38393.1±0.005
8.00	94.2	0.2520±0.0011	1,740±50	1,910±50	3.450±0.005	3.770±0.005	9.275±0.001	0.050±0	34904.3±0.005	38314.5±0.005
10.00	94.4	0.2480±0.0014	1,600±50	1,820±50	1.780±0.005	2.058±0.005	15.618±0.001	0.048±0	33139.6±0.005	37696.3±0.005
25.00	89.7	0.2452±0.0018	1,480±50	1,680±50	1.782±0.005	2.140±0.005	20.090±0.001	0.047±0	31358.2±0.005	35595.8±0.005

Table 3. Hardness and Tensile Properties of 6061 Aluminum Alloy Aged at 220 Celsius

Aging Time (hrs)	Hardness (R_E)	Tensile Properties								
		d_0(inch)	$P_{0.2}$ (lbs)	P_{ts} (lbs)	L_0 (inches)	L_f (inches)	%EL	Ao (in^2)	$\sigma_{0.2}$ (psi)	σ_{ts} (psi)
0.00	21.5	0.2503±0.0003	375±50	1,100±50	1.614±0.005	2.319±0.005	43.680±0.001	0.0492±0	21350.00±0.005	30500.00±0.005
0.01	23.9	0.2510±0.0008	400±50	1,080±50	1.851±0.005	2.304±0.005	24.473±0.001	0.0495±0	24668.50±0.005	32756.53±0.005
0.10	57.3	0.2507±0.0006	1,050±50	1,500±50	1.696±0.005	2.243±0.005	32.252±0.001	0.0493±0	37305.95±0.005	40144.45±0.005
0.25	77.8	0.2510±0.0015	1,220±50	1,620±50	1.856±0.005	2.179±0.005	17.403±0.001	0.0495±0	36396.15±0.005	39631.36±0.005
0.50	89.5	0.2511±0.0011	1,840±50	1,980±50	1.821±0.005	2.048±0.005	12.466±0.001	0.0495±0	36878.14±0.005	39909.22±0.005
1.00	91.0	0.2493±0.0004	1,800±50	1,960±50	3.473±0.005	3.731±0.005	7.429±0.001	0.0488±0	27260.73±0.005	31155.12±0.005
2.00	91.5	0.2502±0.0001	1,825±50	1,975±50	3.498±0.005	3.734±0.005	6.747±0.001	0.0491±0	31745.37±0.005	36425.77±0.005
3.00	87.4	0.2480±0.0007	1,330±50	1,520±50	3.452±0.005	3.698±0.005	7.126±0.001	0.0483±0	28997.13±0.005	34175.19±0.005
4.00	83.0	0.2500±0.0006	1,560±50	1,790±50	3.520±0.005	3.759±0.005	6.790±0.001	0.0491±0	26904.46±0.005	32407.64±0.005
6.00	86.4	0.2490±0.0010	1,400±50	1,650±50	1.978±0.005	2.191±0.005	10.768±0.001	0.0487±0	26710.07±0.005	32463.01±0.005
8.00	82.8	0.2534±0.0038	1,320±50	1,590±50	1.852±0.005	2.069±0.005	11.717±0.001	0.0504±0	22814.71±0.005	29758.32±0.005
10.00	76.7	0.2547±0.0021	1,300±50	1,580±50	1.866±0.005	2.107±0.005	12.915±0.001	0.0492±0	21350.00±0.005	30500.00±0.005
25.00	78.9	0.2515±0.0013	1,150±50	1,500±50	1.823±0.005	2.025±0.005	11.081±0.001	0.0495±0	24668.50±0.005	32756.53±0.005

IV. Calculation

A. Ao and its RMS uncertainty u_{Ao}

B. $\sigma_{0.2}$ and its RMS uncertainty $u_{\sigma 0.2}$

C. σ_{ts} and its RMS uncertainty $u_{\sigma ts}$

D. %EL and its RMS uncertainty U_{EL}

Determination of the Tensile Properties

Table 4. RMS Values of Ao, $\sigma_{0.2,}$ σ_{ts} , %EL

Ao(in^2)	u_{Ao}	$\sigma_{0.2}$ (psi)	$u_{\sigma 0.2}$	$\sigma_{ts\ (psi)}$	$u_{\sigma ts}$	%EL	u_{EL}
0.051687	0.001289	6384.6	967.35	19695.4	967.35	29.129	0.060497
0.051768	0.000645	7340.5	965.851	19510.2	965.8513	28.538	0.061502
0.051687	0.000725	7351.9	967.35	19734.1	967.35	26.293	0.058693
0.049063	0.001256	9579.6	1019.10	22828.0	1019.10	16.583	0.054181
0.049377	0.000315	20961.2	1012.61	30884.8	1012.61	13.899	0.054005
0.051406	0.000828	32875.8	972.65	36961.0	972.65	16.952	0.056891
0.05051	0.000804	34250.9	989.91	37814.6	989.91	12.013	0.055118
0.049338	0.000236	36483.3	1013.42	39726.3	1013.42	11.512	0.054079
0.049063	0.00051	34140.1	1019.10	37197.5	1019.10	2.801	0.053735
0.050009	0.000357	34393.8	999.81	38393.1	999.81	10.054	0.054754
0.049851	0.000435	34904.3	1002.99	38314.5	1002.99	9.275	0.039822
0.048281	0.000545	33139.6	1035.61	37696.3	1035.61	15.618	0.057058
0.047197	0.000693	31358.2	1059.39	35595.8	1059.39	20.090	0.058115

Aging behavior of the 6061 aluminum alloy

The hardness versus aging time curves for aluminum and copper alloy aged 200 and 220 Celsius. In Figure 1, GP1 zones are not completely shown because 200 and 220 Celsius degrees are above the GP1 solvus temperature. In GP1 zones, the hardness increases by impeding dislocation movement and coherent disks are formed. Further aging creates GP2 zones that increase the hardness still more by making dislocation movement still more difficult. A maximum in hardness is reached with still more aging time at 200 Celsius degree and semicoherent is formed. Aging beyond the hardness peak dissolves the GP2 zones and coarsens the semicoherent phase and causes the decrease in the hardness of the alloy. After semicoherent zones, equilibrium phase is incoherent.

V. Discussion (Questions)

1. During the initial hardening, the precipitation structure is supersaturated solid-solution. In GP1 zones, the hardness increases by impeding dislocation movement and coherent disks are formed. During secondary hardening, at the peak of strengthening, the semicoherent phase forms. Aging beyond the hardness peak dissolves the GP2 zones and coarsens the semicoherent phase and causes the decrease in the hardness of the alloy. After semicoherent zones, equilibrium phase is incoherent.

2. The nature of the precipitates for hardening 6061 aluminum alloy is Mg_2Si. Silicon is almost insoluble in aluminum at temperature below 200 Celsius degrees. In unalloyed aluminum, transmutation-produced silicon forms a precipitate phase of elemental silicon. If free magnesium is available in solid solution in aged 6061 which already contain thermally induced Mg_2Si phase, there is no free magnesium and the transmutation produced silicon forms particles of elemental silicon which coexist with the Mg_2Si precipitate. These precipitates harden the alloy.

3. The final strength of the alloy will be significantly lower than that which is expected with heat treatment within the normal range. When 6061 aluminum alloy is heat treated using a temperature below the normal range, the solution is not complete, in which the maximum amounts of magnesium and silicon were not taken into solid solution and there is a reduction in concentration of the solid solution.

References:

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