STRENGTHENING MECHANISMS IN THE AGED 2024 AND 7075 ALUMINUM ALLOYS

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Abstract Aluminum 2024 and 7075 alloys which are widely used in aerospace and marine applications were chosen to investigate their strengthening mechanisms. Using differential thermal analysis (DIA), metallography and tension tests, the best solutionizing conditions were determined to be 500±5°C and 2 hours for 2024 and 480±5°C and 1 hour for 7075 alloy. Aging was performed in the range of 100 to 200°C for various times. It was concluded that the maximum strength in 2024 alloy was developed at 180-190°C after 10 hours and in 7075 alloy at 120°C for 28 hours. In order to determine the strengthening mechanisms in these alloys qualitatively, the T8 treatment (cold work plus aging) was carried out. The results show an increase in the mechanical strength of 2024 alloy whereas the 7075 alloy was not affected appreciably by cold working. It can be concluded that the strengthening mechanism in the 2024 alloy is due to the stress field around the precipitates, whereas in the 7075 alloy it is due to chemical strengthening.

چکیده رسوب سختی یکی از روشهای مقاوم کردن بعضی از آلیاژهای صنعتی مانند آلیاژهای آلومینیوم میباشد. مقاوم شدن بیشتر در نتیجه برخورد نابجائی‌ها با ذرات پراکنده رسوبات حاصل میشود. در این پژوهش آلیاژهای پیر سخت‌شونده ۲۰۲۴ و ۷۰۷۵ آلومینیوم بعلت اهمیت در صنایع هوائی، دریائی و نظامی انتخاب شده اند و سعی شده است که با استفاده از روش آنالیز حرارتی جزء به جزء (DTA) و تست کشش مناسبترین درجه حرارت حل کردن و نیز تاثیر کار سرد قبل از عملیات حرارتی پیرسختی بر روی خواص مکانیکی این دو آلیاژ تعیین گردد. نتایج آزمایشی نشان میدهد که کارسرد باعث افزایش مقاومت مکانیکی آلیاژ ۲۰۲۴ میشود، اما این عمل بر روی آلیاژ ۷۰۷۵ تاثیر قابل ملاحظه ای ندارد. لذا مکانیزم رسوب سختی در این دو آلیاژ متفاوت است و احتمالاً در آلیاژ ۲۰۲۴ وجود میدانهای تنسی اطراف فازهای رسوب باعث مقاوم شدن این آلیاژ است در صورتیکه در آلیاژ ۷۰۷۵ مقاوم شدن شیمیایی مکانیزم اصلی را تشکیل میدهد.

INTRODUCTION

Particle strengthening in a metallic matrix depends on many factors such as size, shape, number density, distribution, lattice mismatch, mechanical properties of particles and matrix, and also on the surface energy and bond between these phases. In the early stages of precipitation, particles have a coherency with the matrix and whether elastic energy or surface energy is dominant, disc shape or spherical particles will be persistant. With the growth of particles, elastic strain due to the mismatch between particles and matrix increases and so does the elastic energy. Mott and Nabarro[1] estimated an increase in stress of the elastic field as $\Delta\sigma = 2\,G.\epsilon.f$, where $\Delta\sigma$ is the increase in strength, f is the volume fraction of particles, G is the shear modulus and ϵ is a criterion of elastic strain around the particles. When the effects of crystal mismatch on the strain field are minimized the increase in

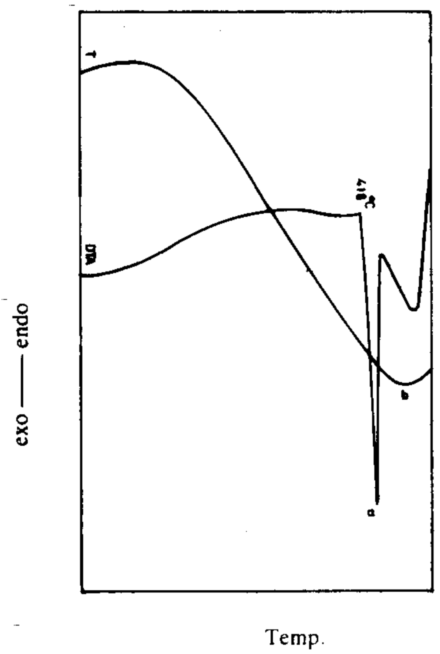

Figure.1. Differential thermal analysis for the standard sample (Pure Zn).

The curve marked T shows temperatue of the sample and the one marked DTA indicates direction of endothermic or exothermic transformation. Point "a" indicates melting and Point "b" locates the furnace shut off.

strength is mainly due to chemical bonding between precipitates and the matrix[2].

Chemical bonding can be due to differences in the elastic moduli, surface energy, Peierls stress of phases and disordering of the particle structure when a dislocation shears through [3-5]. Since several of these variables act simultaneously, strengthening is a superposition of several mechanisms in the 2024 and 7075 aluminum alloys. However, qualitatively, it is possible to distinguish between the major mechanisms by a suitable cold work and aging treatment, relying on the fact that chemical strengthening is not affected appreciably by cold working.

To act systematically, solutionizing and optimum aging conditions (temperature and time) should be verified first. Although these data may be available for some alloys [6] minor changes in the homogeneity or composition affect the results. Soaking temperature must be chosen so that none of the binary or multicomponent eutectics melts, i.e., the alloy should not be locally burnt. The lower limit of the temperature is chosen by final mechanical properties and corrosion resistance of the alloy. Generally, the wrought sheets up to 5mm in thickness are solutionized near the upper temperature limit because the best mechanical strength will result in the successive aging treatment.

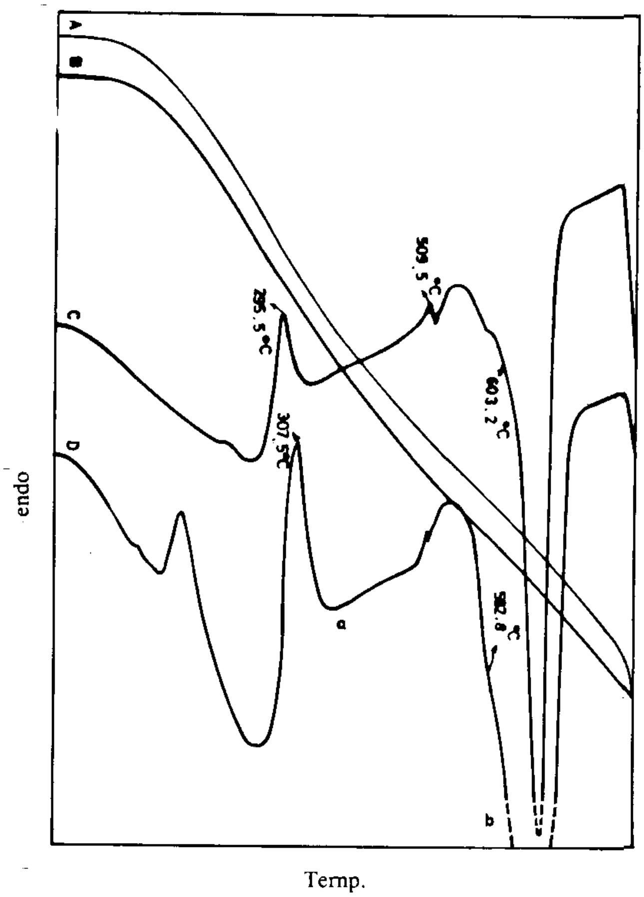

Figure.2. Differential thermal analysis for the 2024 alloy. Curves A and C show temperature and DTA for the as received alloy. Curves B and D are for the supersaturated alloy. Point "a" indicates resolution of precipitates and Point "b" shows melting.

The possible phases [7,8] in the wrought 2024 alloy are $(Fe,Mn)_3Si_2Al_{15}$, $CuMg_4Al_6$, Mg_2Si, $CuMgAl_2$, Cu_2FeAl_7, and $Cu_2Mn_3Al_{20}$. These precipitates can be divided into two groups. The first one includes the precipitates which have only one or more elements such as copper, lithium, magnesium, silicon and zinc. The second group contains undissolved precipitates of elements such as iron, manganese and nickel.

In the ternary phase diagram of Al-Zn-Mg, alloy 7075, low temperature eutectic com-

Table 1. Mechanical Properties of Aged 2024 Alloy at 120°C with Different Amounts of Cold Work

time,hr	% R.A.	σ_u,MPa	σ_y,MPa	Sample No.
2.00	0	451	294.7	1
4.3	0	453.5	298.6	2
9.6	0	456.8	303.5	3
20.00	0	468.3	306.4	4
30.00	0	176.5	115.9	5
2.00	4.5-5.5	464.8	371.1	6
4.3	4.5-5.5	471.8	362.2	7
9.6	4.5-5.5	482.9	386.1	8
20.00	4.5-5.5	482.8	390.8	9
30.00	4.5-5.5	183.5	146.5	10
2.00	11-12	483.4	418.3	11
4.3	11-12	499.3	430.3	12
9.6	11-12	507.2	439.8	13
20.00	11-12	517.9	446.7	14
30.00	11-12	198.5	165.5	15
2.00	14-15	520	478	16
4.3	14-15	527.2	473.6	17
9.6	14-15	526.5	473.1	18
20.00	14-15	531.8	471.6	19
30.00	14-15	176.5	115.6	20

Table 2. Mechanical Properties of Aged 7075 at 120° C with Different Amounts of Cold Work

% R.A.	**time,hr**	**σu,MP.a**	**σy, MPa**	**Sample No.**
0	0	301.5	122.6	1
0.7-1.0	2	387.7	302.3	2
0.7-1.0	4	404.3	318.6	3
0.7-1.0	10	432.7	372.7	4
0.7-1.0	20	441.2	388.6	5
0.7-1.0	25	444.5	388.5	6
0.7-1.0	30	463.5	420.9	7
2.0-3.0	2	401.3	331.8	8
2.0-3.0	4	413.6	346.7	9
2.0-3.0	10	425.2	378.4	10
2.0-3.0	20	438.6	384.3	11
2.0-3.0	25	434.5	395.4	12
2.0-3.0	30	455.5	415.2	13
4.0-5.0	2	394.9	348	14
4.5-5.0	4	404.3	356.5	15
4.5-5.0	10	425.5	392.9	16
4.5-5.0	20	432.8	392.9	17
4.5-5.0	25	405.9	393.8	18
4.5-5.0	30	449.8	419.2	19

pounds are not accurately determined. A quasibinary eutectic of Al-$Mg_3Zn_3Al_2$ at the precise ratio of Zn/Mg=2.5/1 occurs at 489°C. Also the binary eutectic Al-$MgZn_2$ occurs at 475°C. A ternary eutectic Al-$Mg_3Zn_3Al_2$-$MgZn_2$ occurs at 475°C and another Al-Mg_5Al_8-$Mg_3Zn_3Al_2$ occurs at 450°C. The melting point of a quaternary eutectic Al-$Mg_3Zn_3Al_2$ - $CuMgAl_2$ - $MgZn_2$ is 475°C [9]. Many phases may be formed in Al-Zn-Mg, depending on the composition [8-10]. There are three hardening phases, $CuMgAl_2$. MgZnCuAl and $MgZn_2$. The second and the third one have a considerable effect on strengthening of the alloy but start to dissolve at 475°C [10]. Therefore in the presence of low melting eutectic compounds and different dissolvable phases, a proper solutionizing temperature is extremely vital.

EXPERIMENTAL PROCEDURES

(a): Materials: The materials used in this work were 2024 and 7075 Al alloys with thicknesses of 3.2 and 0.508 mm, respectively. The composition (weight %) of the alloy 2024 was 4.5%Cu, 1.5%Mg, 0.6% Mn and the balance was Al. This alloy is produced as sheets plates and bars. The chemical composition of the alloy 7075 was 5.6%Zn, 2.5%Mg, 1.6%Cu, 0.3% Cr and the balance was Al. This alloy is produced as cladded sheets and plates for improving corrosion resistance. In addition to the wrought alloy, a cast 7075 alloy from Iralco was also tested.

(b): Differential Thermal Analysis: DTA was used to determine the upper temperature limit for solutionizing , the temperature at which one of the phases starts to melt. The instrument starts heating up the sample and records any exothermic or endothermic reaction which occurs. At the same time the temperature increase is plotted simultaneously, so the temperature at which a reaction occurs can be determined. The sensitivity of tempeature measurement was ±5°C(±0.5 milivolt). For instrument calibration and establishing the direction of endothermic and exothormic processes, pure zinc (99.999%) which has an endothermic melting at 418°C was employed as the standard sample (Figure 1). Two pieces of 2024 alloy were used for DTA studies. One

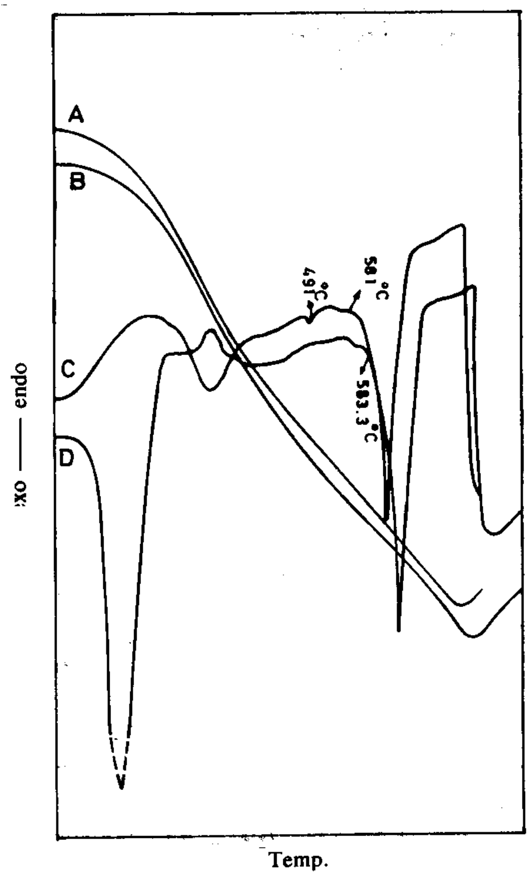

Figure.3. Differential thermal analysis for the 7075 alloy. Curves A and C show temperature and DTA for the cast alloy. Curves B and D are for the as received O-Alclad alloy. A nonequilibrium melting occurs in the cast alloy at 491°C.

was in the as received condition (T_3 Treatment) and the other was in the supper-saturated condition (Figure 2). Also, two samples of 7075 alloy, one as received 7075-O-Alclad and one cast 7075 alloy with a non-homogeneous structure were used (Figure 3). For both alloys the soaking temperature was determined to be 500° C±5°C as will be discussed in the next section.

(c): Heat Treatment: Electrical furnances with the accuracy of ± 5°C. and±1°were used. . Quenching media was tap water at ≃3°C. A series of heat treatment cycles were performed to determin ethe proper solutionizing time and aging conditions.

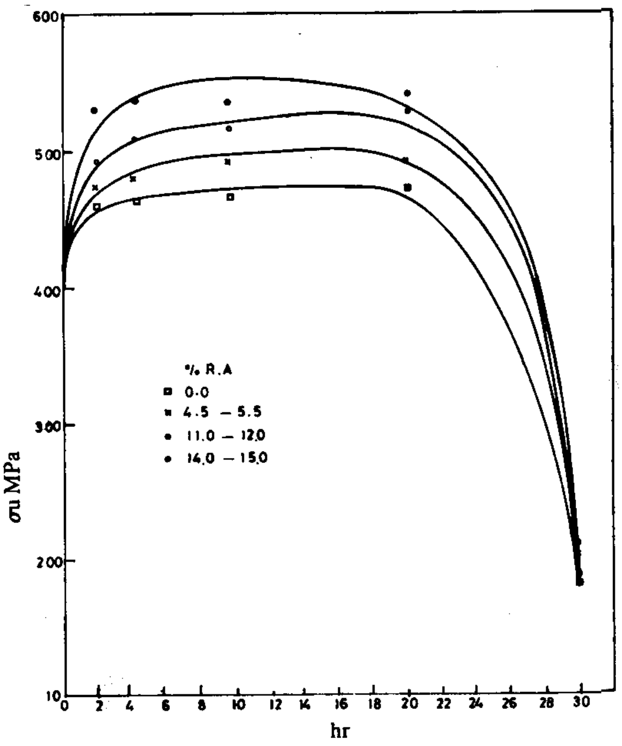

Figure.4. Tensile strength of the 2024 alloy versus aging time and different amount of cold work prior to aging.

(d): Tension Test: For mechanical testing , standard (ASTM-E-8) tensile samples cut by tensilklut lathe were used. The samples were tested with a 5 ton Instron machine at room temperature. Cross-head speed was 0.5 cm/min. Cold working of some of the samples prior to aging was also performed on Instrom.

(e): Effect of Cold Work on aging: Twenty one standard samples of 2024 alloy were solutionized at 500°C for 2 hours and quenched. They were divided into four groups of five specimens and one group of one sample. The last sample was tested without any cold work or aging. The first group with five members were only aged at 120°C for different aging times and then tested. The other three groups received 4.5.-5.5, 11-12 and 14-15 percent cold work and then were aged at 120°C at different aginig times. Results of these tests are listed in Table 1 and depicted in Figure 4.

Similarly, nineteen tension samples of 7075 alloy were solutionized and quenched. These samples were divided into three groups of six specimens and one group of one specimen.

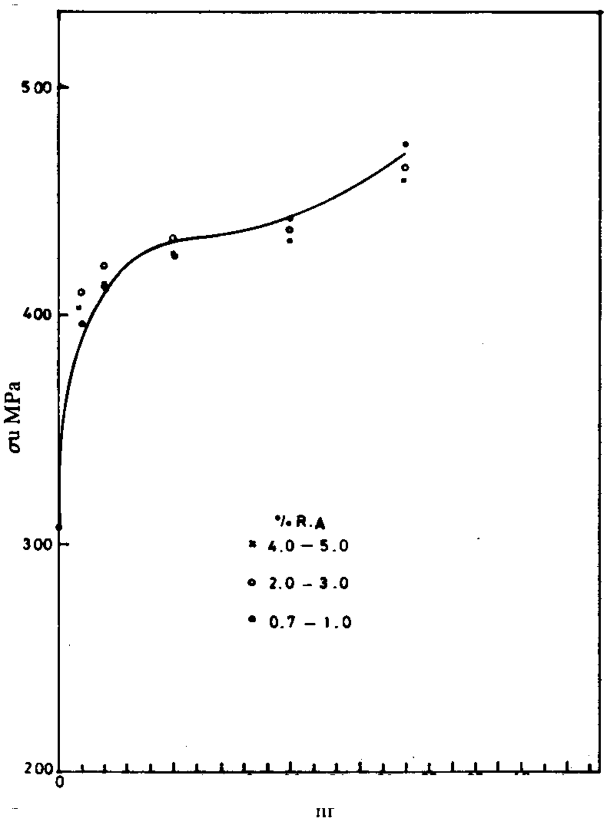

Figure.5. Tensile strength of the 7075 alloy versus aging time and different amount of cold work prior to aging.

The last sample was tested without any treatment, while the other samples received 0.7-1, 2.5-3 and 4-5 percent cold work, aged at 120°C for different times and tested in tension. Results are listed in Table 2 and plotted in Figure 5.

RESULTS AND DISCUSSION

(a) Determination of Solutionizing and Aging Conditions:

For the as received and supersaturated 2024 alloy, DTA shows that an equilibrium eutectic melting starts at 509°C in both samples as shown in Figure 2. This indicates that solutionizing and supersaturation does not change this melting temperature, only the quantity of melt is decreased by supersaturation. These data are consistant with other works [12] (Figure 6). Therefore, 500°C seems to be a good choice for soaking.

For 7075 alloy the situation is a little different (Figure 3). Nonhomogeneous 7075 alloy (cast) has a non-equilibrium eutectic at 490°C, but the homogeneous alloy starts to melt at about 530°C. These data are a little different from those given in Reference 13, (Figure 6). It is concluded that minor changes in alloying elements and structure may appreciably affect solutionizing conditions of 7075 alloy. Therefore 500°C seems to be a conservative soaking temperature if the homogeneity is not assured.

A solutionizing temperature of 500°C±5°C was chosen for both 2024 and 7075 alloys used in this work. Solutionizing time depends on the homogeneity and thickness and it is chosen to produce the highest mechanical strength in the supersaturation condition. For this purpose several samples of each alloy were solutionized for different times (30 to 240 minutes) and quenched. Tension test was carried out and the variation of tensile strength (σu) versus solutionizing time wasplotted.For the 2024 alloy the highest σu was observed to occur after 120 minutes at 500°C [13]. Maximum in σu was attained after 60 minutes in the 7075 alloy. These results are consistant with other work [6]. Heating for longer times results in grain growth and a slow decrease in σ_u [13].

Aging was performed in the range of 100 to 200°C for different times and it was concluded that the maximum strength in 2024 alloy was developed at 180-190°C between 10 to 20 hours and in 7075 alloy at 120°C in 28 hours.

(b): Effect of Cold Work on Strengthening Mechanisms:

Figure 4 shows that the strength of 2024 alloy is highly affected by the amount of cold work prior to aging. The percent increase in σ_u is almost the same as that of the applied cold work, i.e., a 15% C.W. has caused a 15% increase in σu. The following values are derived from Table 1.

C.W.%	σ%
4.5-5.5	5.5-6
11-12	
14-15	

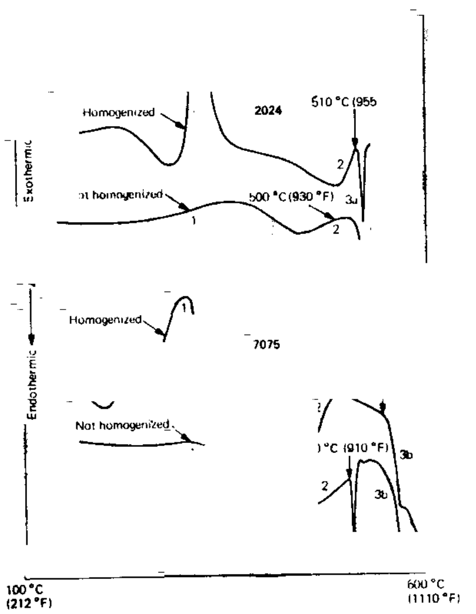

Fig. 6. DTA curves at 20°C/min (36°F/min) heating, indicating temperatures for easily identified beginning of melting (shown by arrows). Significant curve inflections are (1) precipitation from saturated solid solution, (2) re-solution of precipitated phase (s), and (3) melting. Equilibrium eutectic melting for 2024 is indicated by (3a); equilibrium solidus melting for 7075 by (3b), and nonequilibrium eutectic melting for 7075 by (3c).

Figure.6. Differential thermal analysis for 2024 and 7075 alloys, published by John E.Hatch (Reference 12).

Remembering $\Delta\sigma \simeq 2g.f.\epsilon$ in the case of strain field hardening, it may be concluded that the main strengthening mechanism in 2024 alloy is due to the elastic energy around the particles. The difference between the atomic radii of Al and Cu (Δr) is about 13%, and the misfit between the precipitates and the matrix is high, causing planar (disk like) nuclei to be formed in order to offset the high elastic energy due to the mismatch. However if a supersaturated 2024 alloy is strain hardened, nucleation sites are abundant and upon aging (T8 Treatment) more particles will be formed in the preferred orientations which are planes and directions of lowest elastic modul and G.P. zones are plate-like. TEM micrographs are available [14] which confirm the aforementioned effects of cold work on the redistribution of particles in 2024 alloy. A literature survey confirmed that the 2024 alloy in the T_8 temper shows the highest strength and the yield strength may be increased by as much as 35% as compared with the T_6 temper [15].

Cold work did not produce any appreciable effect on 7075 alloy, (Figure 5). For short aging times (10 hours) there is a small increase in the yield and tensile strength with increasing C.W.%, but the trend is reversed at longer aging times. This is probably due to the fact that particles, when small, are coherent and upon aging they become incoherent, changing the energy mode from elastic to surface energy. Δr for Al and Zn is $\simeq$3% and lattice misfit seemingly is not high in 7075 alloy, and the particles acquire rounded shapes (most probably spherical G.P. zone [16] to keep the surface energy as low as possible. Therefore cold work does not function in 7075 alloy similar to that of 2024 alloy, and the strengthening mechanism is of the chemical nature. It is not surprising that T_8 is not common temper for the 7075 alloy and this alloy is used in either T_6 (for the highest strength) or T_7 temper (for excellent resistance to SCC [15,16].

CONCLUSIONS

1)- DTA is a powerful instrument to determine solutionizing temperature.

2)- Solutionizing temperature is dependent on homogeneity and it is less for the cast 7075 alloy than the wrought alloy.

3)- Maximum strength in 2024 alloy is achieved by the T_8 (cold work + aging at 180°C) temper.

4)- The T_8 temper does not increase the strength of the 7075 alloy compared to its strength in the T_6 temper.

5)- It is concluded that the strengthening mechanism in the 2024 alloy is due to elastic straining and in the 7075 alloy to chemical bonding.

These conclusions are based on the experimental results of this work and the TEM studies of other investigators who showed plate like G.P. zones in 2024 alloy and spherical one in 7075 alloy.

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