Effect of Delayed Aging on Mechanical Properties of an Al-Cu-Mg Alloy

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The effect of delayed aging on mechanical properties is characteristically found in Al-Mg-Si alloys. "Delayed aging" refers to the time elapsed between solutionizing and artificial aging. Delayed aging leads to inferior properties. This effect was investigated in an Al-Cu-Mg alloy (AU2GN) of nominal composition Al-2Cu-1.5Mg-1Fe-1Ni as a function of delay. This alloy also showed a drop in mechanical properties with delay. The results are explained on the basis of Pashley's kinetic model to qualitatively explain the evolution of a coarse precipitate structure with delay. It is found that all the results of delayed aging in the Al-Cu-Mg alloys are similar to those found in Al-Mg-Si alloys.

Keywords Al-Cu-Mg alloy, artificial aging, delayed aging, mechanical properties, solutionizing

1. Introduction

The alloy of nominal composition Al-2Cu-1.5Mg-1Fe-1Ni (AU2GN) is designed for elevated temperature applications up to about 523 K in aeroengine components. This alloy is subjected to delayed aging. The term "delayed aging" refers to the severe impairment in hardness and tensile properties (ultimate tensile strength (UTS) and yield strength (YS) due to a delay between solutionizing and artificial aging. The delayed aging effect was observed in Al-7Si-0.3Mg alloy.[1,2,3]

Pashley *et al.*[4] have shown that in an Al-Mg-Si quasi-binary alloy, *i.e.*, Al-1.2% Mg_2Si wrought alloy, the precipitate structure coarsens with the average length of Mg_2Si precipitates, increasing from 22 to 48 nm when the alloy is subjected to a delay of 0 to 72 h between solutionizing and artificial aging. Their study[4] also shows that when Cu was added to the alloy, partial inhibition of delayed aging took place. A later study[5] showed that delayed aging can be completely suppressed by trace additions of Cd, In, and Sn in Al-7Si-0.5Mg cast alloy. The same study[5] extended Pashley's kinetic model[6] to explain the effect of trace additions.

During commercial processing, inordinate and unscheduled delays take place between solutionizing and artificial aging. Minor variations occur between batch-to-batch processing, such as those in solutionizing temperature, delay in quenching, delay in aging, and aging temperature. In an earlier study,[7] the effect of quench delay on fatigue life of alloy AU2GN was studied, and it was found that the quench delay reduces fatigue life. Based on the above study, quench delays were kept to less than 100 s. Similarly, delays between solutionizing and aging treatments were noticed in the shop floor practice, resulting in erratic results. Thus, there is a need to systematically understand the effect of delayed aging on the properties of AU2GN. Therefore, the present work was taken up to study this topic.

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2. Experimental Details

Samples were solutionized at 808 K for 6 h, water quenched, and subjected to a delay of 0, 2, and 48 h before artificial aging at 478 K for 22 h. Heat treatment details are shown in Table 1. Temperatures were accurate to within ±5 K and quench delays in all cases were within 10 s. The heat treatment was carried out in an air circulating pit furnace.

Samples of appropriate dimensions were prepared from cylindrical blanks for various tests, namely, hardness ($25 \times 25 \times 25$ mm), tensile (5-mm gauge diameter and 25-mm gauge length), and fatigue (4-mm gauge diameter and 20-mm gauge length). Hardness testing was carried out on a Karl Frank (Weinheim, Germany) (GmbH) brinnel hardness testing machine with a 2.5-mm ball and a load of 62.5 kg. An Instron (United Kingdom) universal testing machine (model 1116) was used to carry out tensile tests at room temperature at a nominal strain rate of 10^{-3} s^{-1}.

High-cycle fatigue (HCF) tests were carried out to failure using a rotating beam testing machine. The applied bending stress was 260 MPa (~65% of the UTS) and the speed of rotation was 3,000 rpm. Stress rupture tests were carried out using a Satec (Grove City, PA) testing machine at 470 K and at a stress of 190 MPa.

3. Results and Discussion

Table 2 shows the results of the mechanical properties of the alloy AU2GN in 0, 2, and 48 h delay between solutionizing and artificial aging, respectively. The tensile properties decrease as a function of delay time from 0 to 48 h through 2 h delay.

Figure 1 shows the delayed aging curve and also the natural aging curve. It is observed that hardness drops with the delay in just 30 min. Further, the hardness increases in just 30 min during natural aging to a value of 80 BHN.

The fatigue life significantly dropped from 1.535×10^5 cycles (0 h delay) to 4.85×10^4 cycles (48 h delay). Similarly, the stress rapture life at 478 K with a stress of 190 MPa dropped significantly from 120 plus to 48 h.

The above behavior can be explained based on Pashley's kinetic model,[6] wherein the evolution of a coarse precipitate structure is predicted qualitatively as a function of delay. Pashley's kinetic model is a model for two-step aging, wherein the

Table 1 Heat treatments given to alloy AU2GN

Designation	Solutionizing treatment	Cooling medium	Delay caused before aging	Aging treatment
D0	808 K/6 h	water quenching	0 h	478 K/12 h
D2	808 K/6 h	water quenching	2 h	478 K/12 h
D48	808 K/6 h	Water quenching	48 h	478 K/12 h

Table 2 Mechanical properties of different delayed and aged conditions of the alloy AU2GN (each result is an average of three tests)

Properties	D0	D2	D48
Tensile			
0.2% proof stress (MPa)	342	339	333
Tensile strength (MPa)	402	382	375
Elongation (%)	9.5	9.5	9.0
HCF properties at room temperature			
Fatigue life (number of cycles) at 260 MPa Stress	1.535×10^5	6.85×10^4	4.85×10^4
Stress Rupture			
Stress rupture life at 478 K	120 h(a)	57 h	42 h
Remarks	specimen did not fail	specimen fractured	specimen fractured

(a) Test discontinued after 120 h

stability of clusters is considered. Clusters, as the name suggests, are an aggregate of solute atoms in the matrix. Clustering takes place during solutionizing and/or after quenching either at room temperature or at the artificial aging temperature just prior to precipitation.

In Pashley's model, the stability of these clusters, after storing the alloy at lower temperature (T_1) followed by aging at a higher temperature (T_2), is considered. The stability criterion is based on the increased rate of arrival of solute atoms to the cluster as compared to the rate of evaporation of solute from the clusters. Using curvature effects, the stability criterion can be derived as follows:

$$(A / B)\bar{r} \ln S > K \quad \text{(Eq 1)}$$

where

$\bar{r}$ = mean cluster radius;
S = supersaturation = $[W(1 - a)]/C_2$
W = weight of solute/unit volume,
α = fraction of solute in clusters, and
C_2 = concentration of solute in equilibrium with a flat interface;
A = coefficient that determines the rate of arrival of solute to the clusters and is proportional to the diffusion coefficient D and excess vacancies X(*AaDaX*); and

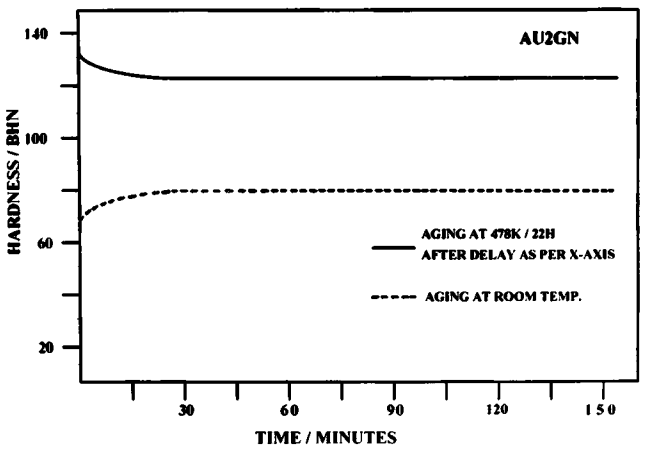


Fig. 1 Delayed aging curve and natural aging curve for the alloy AU2GN

$$K = (2\gamma V_m) / RT \quad \text{(Eq 2)}$$

V_m = molar volume of the cluster species,
T = absolute temperature, and
γ = surface energy between the cluster and matrix.

Spherical clusters are assumed in the model. As the volume average of the clusters is considered (the alternate shapes of the clusters will not change the physical reasoning behind the model),

$$(4 / 3)\pi r^3 \rho N_r = \alpha W \quad \text{(Eq 3)}$$

where

N_r = number of clusters/unit volume, and
r = density of the cluster species.

The above equation is a mass balance of solute in the matrix. Under steady-state conditions, when there are no excess vacancies, $A = B$, and the relations are drawn schematically in Fig. 2.

As delay increases, α increases, and one clearly sees in Fig. 2 that with increased α, particularly at $\alpha > \alpha_r$, clusters get destabilized upon artificial aging. If one assumes a Gaussian distribution of clusters, there will be a minimum cluster size r_{min}, mean cluster size r, and maximum cluster size r_{max}. With the size distribution also incorporated, $r_{min} \ln S$ and $r_{max} \ln S$, it can be seen in Fig. 2 that for $\alpha > \alpha r_{max}$, only the large-sized clusters are stabilized at the artificial aging temperature. The term S'[8] is the strenghtening precipitate in Al-Cu-Mg alloys. The nucleation of S' takes place on these large clusters to give a coarse precipitate structure.

Fig. 3(a) shows the microstructure of the sample with 0 h delay. Only the insoluble particles (constituent particles) are observed. Figure 3(b) shows the microstructure of the sample with 48 h delay. Here, not only the insoluble particles but also the coarse precipitate particles are observed. This observation confirms the prediction of Pashley's kinetic model, which predicts

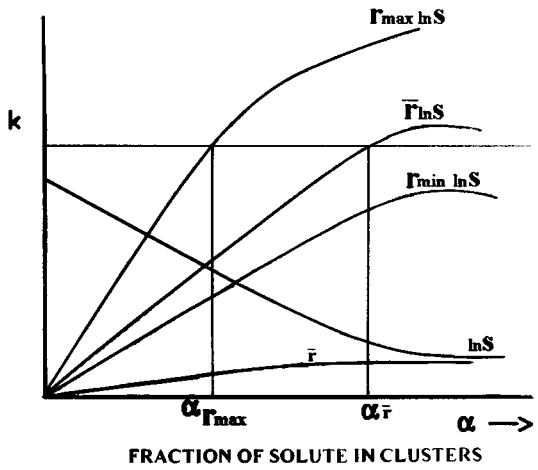


Fig. 2 Stability situation of clusters assuming $A = B$

a coarse precipitate structure with long duration of delay between solutionizing and artificial aging.

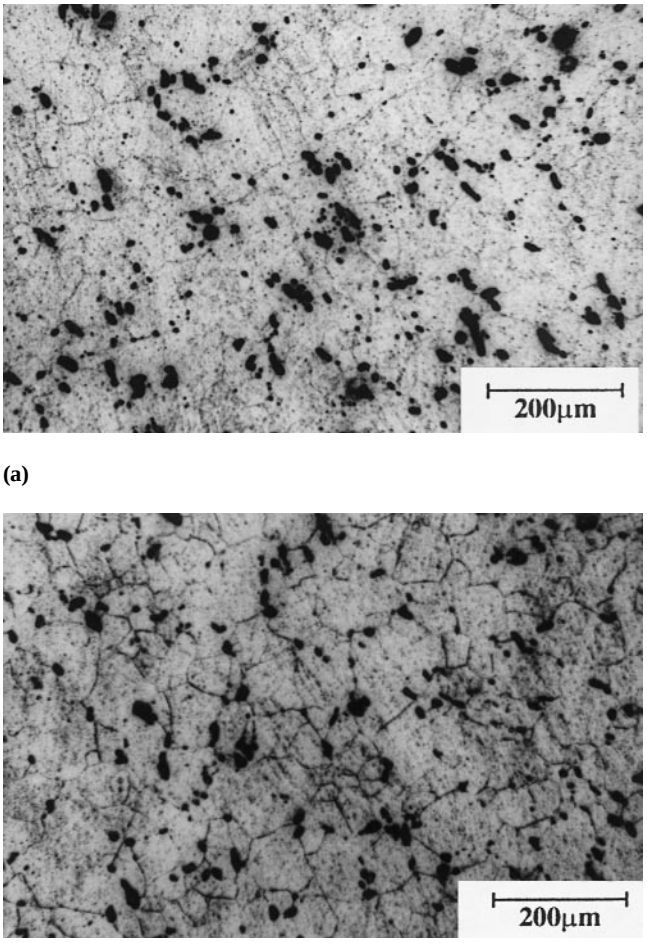
Therefore, as the S' precipitate becomes coarse, the tensile properties (*i.e.*, YS and UTS) will drop as expected with delay, as can be noted in Table 2. This phenomenon also explains the hardness drop with delay illustrated in Figure 1.

Table 2 also shows a drop in HCF life with delay, which can also be explained on the basis of coarse precipitate structure. With delay, as in conditions D2 and D48, a coarse precipitate structure is obtained. This will accentuate planar slip (localized slip),[9] which will lead to early nucleation of fatigue cracks, where as with 0 h delay, a fine precipitate structure prevails, which has the effect of homogenizing the slip, leading to extended fatigue life.[10]

Once again it can be observed from Table 2 that the stress rupture lives for the delayed conditions D2 and D48 are reduced as compared to the conditions without delay (D0). In order to explain these results, the creep mechanisms need to be invoked. The dominant mechanism for creep can be considered to be grain boundary sliding.[11] In view of this, the accommodation of grain boundary sliding is dislocation glide and climb in neighboring grains.[11] If the precipitate is coarse, as in conditions D2 and D48, dislocation glide becomes far easier. Therefore, the material exhibits a high rate of grain boundary sliding, which allows the sample to fail early. When the precipitate structure is fine, as in the D0 condition, accommodation in terms of dislocation glide is more difficult and, thus, inhibits grain boundary sliding.

Further, it can be seen from the natural aging curve, in Fig. 1, that the hardness increases from a value of 64 VHN in the 0 h delayed condition to a value of 80 VHN in an approximate 30 min delay (or aging at room temperature) and maintains the value for a long aging time.

It was already discussed that there is deterioration in engineering properties such as tensile, fatigue, and stress rupture after a delay of 2 and 48 h. Thus, one can take these two observations and correlate the same. This means that once the simple hardness test gives a value of 80 VHN, it can be stated that the engineering properties have deteriorated and the specimens need to be solutionized. In this way, a simple hardness test can become a key output.



(a)

(b)

Fig. 3 Microstructure of the sample with **(a)** 0 h delay and **(b)** 48 h delay

Conclusions

The delayed aging of Al-2Ci-1.5Mg-1Fe-1Ni alloy (AU2GN) impairs the mechanical properties. The observations are consistent with Pashley's kinetic model.

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