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Effect of an electric field applied during the solution heat treatment of the Al–Mg–Si alloy AA6022 on the subsequent natural aging kinetics

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Abstract The influence of a dc electric field $E = 5$ kV/cm applied during the solution heat treatment (SHT) of the Al–Mg–Si alloy AA6022 at 475–552 °C on the subsequent natural aging kinetics was determined employing resistivity. It was found that the increase in the as-quenched resistivity which resulted from application of the field during SHT was retained throughout the natural aging process. An Avrami-type analysis of the natural aging kinetics gave $n_{\text{avg.}} = 0.3$ and $k_{\text{avg.}} = 5 \times 10^{-2}$ $(\text{min}^{-1})^{0.3}$. These values are in qualitative accord with those determined for the Al–Mg–Si–Cu alloy AA6111.

Introduction

In the previous paper [1] it was reported that the application of an external dc electric field $E = 5$ kV/cm during the solution heat treatment (SHT) of the commercial Al–Mg–Si alloy AA6022 increased the as-quenched resistivity ρ_w. This was attributed to an increase in solubility of the pertinent alloying constituents, which resulted from a reduction in the Gibbs free energy of solution ΔG_s by the field. Along with the increase in ρ_w there also occurred an increase in the resistivity corresponding to the subsequent natural aging and in the tensile properties of the T4 temper (natural aging time $t_{NA} \approx 1$ week–1 month). No quantitative determination of the influence of the field on the subsequent natural aging kinetics was however made. The objective of the present work was therefore to determine what effect, if any, an electric field applied *during SHT* of AA6022 had on the subsequent natural aging kinetics.

Experimental

The starting material was the same as that employed in [1] and had the following composition in wt. %.

Mg	Si	Cu	Fe	Cr	Mn	Ni	Mg_2Si	Excess Si
0.58	0.76	0.055	0.13	0.012	0.086	0.006	0.92	0.40

Standard ASTM tensile specimens with 1.2 × 5.1 cm gage section were machined from 0.9 mm thick sheet in the rolling direction and solution heat treated (SHT) in air for 10 min at 475–552 ± 1.5 °C without and with a dc external electric field $E = 5(+)$ kV/cm. The (+) indicates that the specimen was connected to the positive terminal of the power supply. The electrical arrangement is shown in [1]. Following quenching in still water at room temperature the specimens were naturally aged (~ 22 °C) for various times up to 1 month. Conductivity (Σ) measurements were made at selected time intervals employing an AutoSigma Model DL meter. Reported here is the resistivity $\rho = (\Sigma^{-1})$ representing the average (with a scatter of ± 1.5%) of six measurements along the length of the tensile specimen. For the sake of completeness and to aid in the analysis, data from [1] are included in the present paper.

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Results, analysis and discussion

The increase in resistivity ρ with natural aging time t_{NA} is shown in Fig. 1. Evident is an increase in ρ with t_{NA} for each SHT temperature (T_{SHT}), a larger ρ always occurring for SHT with the field compared to without. Similar to Esmaeili et al. (ELP) [2], we will employ the Johnson-Mehl, Avrami, Kolmogorov (JMAK) model [3–5] for evaluating the natural aging kinetics, whereby

$$f_r = 1 - \exp(-kt_{NA}^n) \tag{1}$$

where f_r is the *relative* volume fraction of precipitated clusters at time t_{NA} and k and n are the so-called JMAK parameters. The relative volume fraction is given by

$$f_r = f_{CA}/f_C^* \tag{2}$$

where f_{CA} is the *actual* volume fraction of precipitated clusters at a specific t_{NA} and f_C^* is that at the peak resistivity, where it is presumed that the precipitation process is essentially complete. Rearranging Eq. 2 and taking double logarithms one obtains

$$\ln\ln[1/(1-f_r)] = \ln k + n \ln t_{NA} \tag{3}$$

or

$$\log\log[1/(1-f_r)] = \log(k/2.3) + n \log t_{NA} \tag{3a}$$

Further, we will take

$$f_r = \rho_{C,A}/\rho_C^* = \rho_{C,A}/(\rho_m - \rho_o) \tag{4}$$

where $\rho_{C,A}$ is the resistivity due to precipitated clusters and ρ_C^* is the resistivity component due to the precipitates at the peak resistivity ρ_m, and ρ_o is that due to the Al matrix and includes any undissloved precipitates and insoluble constituents. Moreover, it is assumed that the measured resistivity ρ at any natural aging time t_{NA} is given by the sum

$$\rho = \rho_o + \rho_{C,A} + \rho_{S,A} \tag{5}$$

where $\rho_{S,A}$ is the resistivity due to the soluble constituents remaining in solution at time t_{NA}. Further, the usual assumptions are made that: (a) at ρ_w no precipitated clusters have yet formed (i.e., $\rho_{C,A} = 0$) and (b) at ρ_m there no longer exist any of the dissolved solutes in solution (i.e. $\rho_{S,A} = 0$). The resistivity due to the solutes remaining in solution is given by

$$\rho_{S,A} = \rho_s - \Delta\rho_{S,A} = [(\rho - \rho_o) = \Delta\rho_{S,A}] \tag{6}$$

where $\rho_s = (\rho_w - \rho_o)$ is the resistivity due to the solutes in solution in the as-quenched state and $\Delta\rho_{S,A}$ corresponds to the decrease due to their loss from solution by precipitation. $\Delta\, \rho_{S,\, A}$ is normally proportional to the resistivity due to the precipitates [2], i.e. $\Delta\,\rho_{S,\,A} = \alpha\,\rho_{C,A}$. Substituting $\alpha\,\rho_{C,\,A}$ for $\Delta\,\rho_{S,\,A}$ into Eq. 6 one obtains

$$\rho_{S,A} = (\rho_w - \rho_o) - \alpha\rho_{C,A} \tag{7}$$

Inserting Eq. 7 for $\rho_{S,\,A}$ into Eq. 5 gives

$$\rho_{C,A} = (\rho - \rho_w)/(1-\alpha) \tag{8}$$

Further, substituting Eq. 8 for $\rho_{C,A}$ into Eq. 4 then gives

$$f_r = (\rho - \rho_w)/[(1-\alpha)(\rho_m - \rho_o)] \tag{9}$$

By taking $f_r = 1$ at the maximum resistivity ρ_m, one can obtain α by rearranging Eq. 9 to give

$$(1-\alpha) = (\rho_m - \rho_w)/(\rho_m - \rho_o) \tag{10}$$

The values of α determined from the data in Fig. 1 employing Eq. 10 are plotted versus T_{SHT} in Fig. 2. The

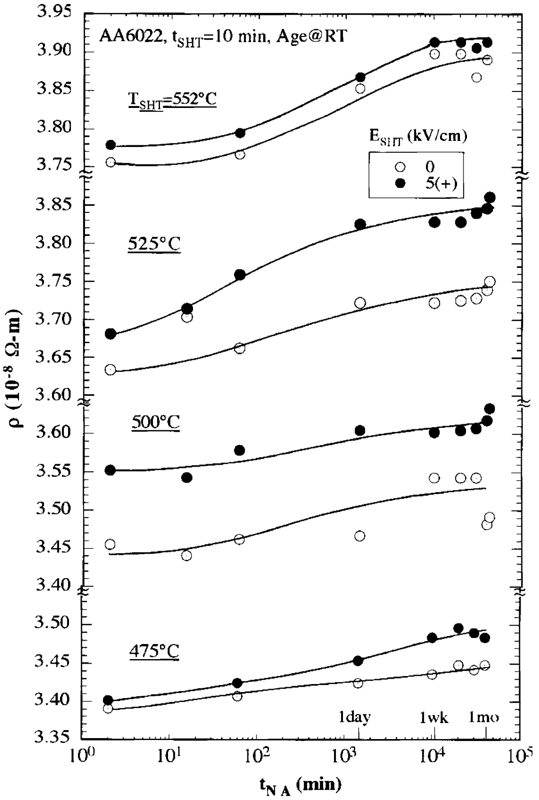

Fig. 1 Resistivity ρ versus natural aging time t_{NA} following solution heat treatment at 475–552 °C without and with an electric field E = 5 kV/cm

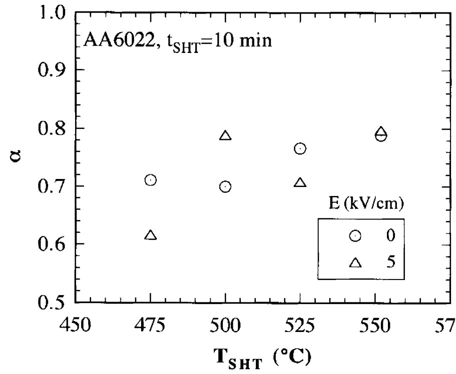

Fig. 2 The parameter α versus the solution heat treatment temperature T_{SHT} without and with an electric field E = 5 kV/cm

average value of α so obtained is 0.74, relatively independent of the applied electric field during SHT and of T_{SHT}. Whether the slightly lower values of α at T_{SHT} = 475 °C represent a real temperature effect is not clear, since they are within the experimental error of the resistivity measurements.

An alternative method for obtaining the magnitude of α is by plotting the resistivity due entirely to precipitated clusters $\rho_c^* = (\rho_m - \rho_o)$ versus the resistivity due entirely to the pertinent solutes in solution $\rho_s = (\rho_w - \rho_o)$. According to Eq. 10 the slope of this plot is α^{-1}. Such a plot is presented in Fig. 3. The data lie along a line through the origin with a slope of 1.3 giving $\alpha = 0.77$, in accord with those obtained using Eq. 10 and taking $f_r = 1$ at $\rho = \rho_m$ (Fig. 2). Again, α is relatively independent of T_{SHT} and electric field. The values of α obtained here for AA6022 are in accord with those ($\alpha = 0.7 \pm 0.1$) obtained for AA6111 [6]. They indicate that electron scattering by the precipitated clusters is approximately 1.3 times greatoer than that due to the corresponding solutes in solid solution.

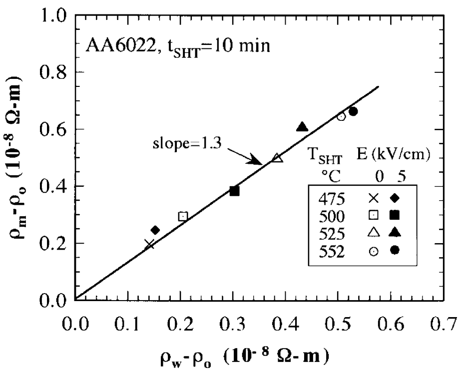

Fig. 3 The resistivity $\rho_c^* = (\rho_m - \rho_o)$ due to the precipitated clusters in the peak-aged state versus that due to the pertinent solutes in solution $\rho_s = (\rho_w - \rho_o)$ as a function of solution heat treatment temperature T_{SHT} and corresponding applied electric field E_{SHT}

A significant portion of the increase probably results from the strain field which exists about the precipitated clusters in Al–Mg–Si alloys [7]. Inserting Eq. 10 for the quantity 1 – α into Eq. 9, one obtains

$$f_r = (\rho - \rho_w)/(\rho_m - \rho_w) \tag{11}$$

An example of the fit of the natural aging kinetics data to the JMAK equation (Eq. 4) employing Eq. 11 is shown in Fig. 4. The magnitudes of the parameters n and k determined from the slopes and intercepts respectively of the least-squares-fit lines in such plots are presented in Fig. 5. The values of n range from 0.18 to 0.50 ($n_{\mathrm{avg.}} = 0.32$) and log k from – 0.6 to – 1.6 $(\mathrm{min}^{-1})^n$ with $(\log k)_{\mathrm{avg.}} = -1.53\ (\mathrm{min}^{-1})^{0.32}$. Both parameters are relatively independent of the SHT temperature and the electric field applied during SHT.

The magnitudes of n and k obtained here for 6022 are qualitatively similar to those (n = 0.59 and log k = – 2.0) obtained for the natural aging kinetics of the Al–Mg–Si–Cu alloy 6111 [6], also employing resistivity. Moreover, these values of n are similar to that (n = 0.5) reported by Esmaeili et al. [2] for the natural aging kinetics of 6111 employing yield stress to monitor the aging process. By converting our values of k to min^{-1} units, they become 4–17 × 10^{-4} min^{-1}, which are in reasonable accord with the value $k = 3.3 \times 10^{-4}$ min^{-1} reported by ELP [2].

The JMAK equation is based on the nucleation and growth rates of a second phase from its parent matrix. The values of the time exponent n for this process generally range between 1 and 4. The low value of n obtained here (0.18–0.59) for the natural aging of Al–Mg–Si alloys suggests that either the nucleation rate or the growth rate (or both) decreases with time. The parameter k in the JMAK equation generally varies as $1/T$, which correspond to an activation energy Q representing the combined nucleation and growth rates.

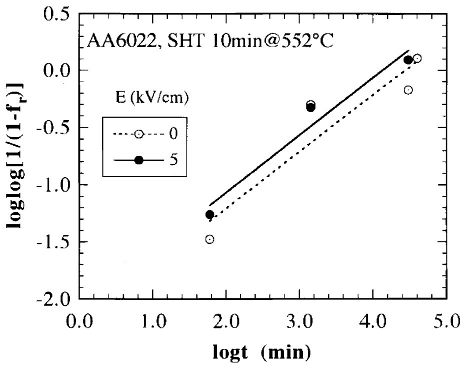

Fig. 4 An example of the fit of the natural aging kinetics to the JMAK equation

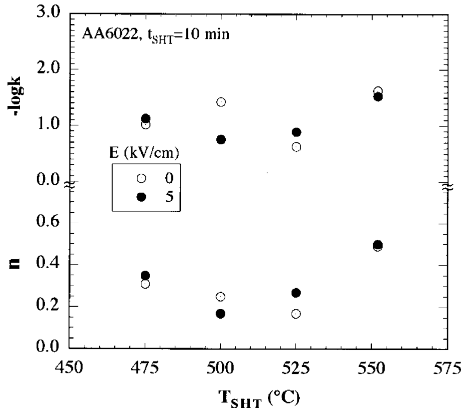

Fig. 5 The JMAK parameters n and k versus the solution heat treatment temperature without and with electric field

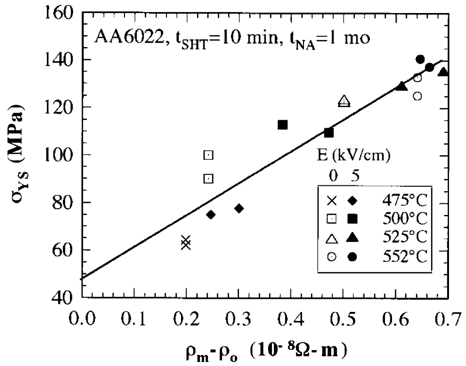

Fig. 6 Comparison of the yield stress in the T4 temper with the resistivity $\rho^*_c = (\rho_m - \rho_o)$ due to the precipitated clusters

The value $Q = 58 \pm 5$ kJ/mole was obtained by ELP [2] for their 6111 alloy aged at 160–220 °C. Since in the present tests aging was only performed at RT, we did not obtain a value of Q for comparison. The present and previous work [1, 6] thus indicates that the application of an electric field during the SHT of Al–Mg–Si alloys increases the solubility, which in turn affects the number and character (size, crystallography or chemistry) of the clusters which occur at the SHT temperature, but has only little if any effect on the kinetics of the subsequent precipitation process during natural aging.

Figure 6 shows for the present 6022 alloy the relationship between the yield stress and the resistivity $\rho^*_c = (\rho_m - \rho_o)$ due to the precipitated clusters for t_{NA} = 1 month. The line though the data points gives

$$\sigma_{ys} = 47.5 + 136 \times 10^8 \rho^*_c \quad \text{MPa and } \Omega - m \tag{12}$$

A similar plot for 6111 gave [6]

$$\sigma_{ys} = 52.4 + 130 \times 10^8 \rho^*_c \quad \text{MPa and } \Omega - m \tag{13}$$

By assigning the intercepts in Eqs. 12 and 13 to ρ_o (ρ_o=3.25 × $10^8 \Omega - m$ and ρ_o = 3.64 × 10^8 $\Omega - m$, respectively), one obtains $\sigma^o_{ys} = 14.6 \times 10^8 \rho_o$ for 6022 and $\sigma^o_{ys} = 14.4 \times 10^8 \rho_o$ for 6111. These values indicate for both 6022 and 6111 that the correlation between yield stress and ρ_o (which is due to the Al matrix) is about an order of magnitude smaller than the correlation between the yield stress and ρ^*_c for the precipitated clusters at the peak-aged state. The correlations between resistivity and yield stress indicate that the atomic and microstructural features which govern electron scattering in these alloys also provide the obstacles opposing dislocation motion.

ELP [2] have proposed that the contribution of the precipitated clusters to the yield stress in the peak-aged state of Al–Mg–Si alloys is given by

$$\sigma^*_c = (\sigma^*_{ys} - \sigma^o_{ys}) = M(F^*)^{3/2}(f^*)^{1/2}/b(2\sqrt{3})^{1/2}\Gamma^{1/2}r^* \tag{14}$$

where M is the Taylor factor, F^* the maximum interaction force between dislocations and an average size cluster of radius r^*, f^*_c the volume fraction of clusters, b the Burgers vector and Γ the dislocation line tension. Since r^* is approximately constant during natural aging of Al–Mg–Si alloys [8] and since F^* is proportional to r^* [2], the intercept force F^* will be constant, so that σ^*_c (and ρ^*_c) are proportional to the volume fraction of precipitated clusters f^*_c. The increase in σ^*_{ys} and ρ^*_c for the peak naturally-aged condition produced by the application of an electric field *during SHT* can thus be attributed to the increase in volume fraction of precipitated clusters f^*_c. The increase in f^*_c with field is concluded to result from the increase in solubility by the field [1]. This suggests an equivalence exists between electric field and SHT temperature regarding the yield stress in the subsequent peak, naturally-aged state (T4 temper). Such equivalence was shown to amount to 10–20 °C in the SHT temperature for starting material in the T4 temper [1, 6]. Whether the same equivalence occurs for other starting material conditions, e.g., homogenized ingot sheet or sheet in the T6 and T7 tempers needs yet to be determined.

Summary and conclusions

The influence of an external dc electric field E = 5 kV/cm applied during the solution heat treatment (SHT) of the commercial Al–Mg–Si alloy AA6022 at

475–552 °C on the subsequent natural aging kinetics was determined by resistivity. The results and conclusions derived therefrom are the following.

(1) The increase in the as-quenched resistivity which resulted from application of the field during SHT was retained throughout the natural aging process.

(2) An Avrami-type analysis of the natural aging kinetics gave $n_{\text{avg.}} = 0.3$ and $k_{\text{avg.}} = 5 \times 10^{-2}$ $(\text{min}^{-1})^{0.3}$, which values were relatively independent of SHT temperature and application of the field. These values are in qualitative accord with those obtained on the Al–Mg–Si–Cu alloy AA6111.

(3) The yield stress in the T4 temper (naturally-aged for ~1 month) correlated with the resistivity according to

$$\sigma_{\text{ys}} = 14.4 \times 10^8 \rho_{\text{o}} + 130 \times 10^8\ \rho_{\text{c}}^* \quad \text{MPa and } (\Omega - \text{m})$$

where ρ_{o} is the resistivity due to the Al matrix and $\rho_{\text{c}}^* = \rho_{\text{m}} - \rho_{\text{o}}$ is that due to the precipitated clusters, ρ_{m} being that corresponding to the T4 temper.

(4) Considering the yield stress in the T4 temper, application of the electric field during SHT is equivalent in effect to an increase of 10–20 °C in SHT temperature.

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