Portevin-LeChatelier Effect of Al-7 mass% Si-Mg Cast Alloys

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Al-7 mass% Si-Mg cast alloys can exhibit the Portevin-LeChatelier (PL) effect if excessive aging is prevented. In the present study, the PL effect of three Al-7Si-Mg cast alloys with 0.11, 0.26 and 0.46 mass% magnesium was compared with that of an Al-7 mass% Si cast alloy. Before conducting the tension test, part of the test alloys was solution treated at 813 K and the remaining were aged at 273 K. The critical strain for the onset of flow instability could be raised by increasing the magnesium content. For the solution-treated specimens tested in the low temperature regime where the critical strain decreases with temperature, the above result should be related to the attractive interaction between silicon and magnesium solutes since the apparent activation energy for the onset of flow instability increases with increasing magnesium content. For the solution-treated specimens tested in the high temperature regime, there occurs an aging effect which is more pronounced with increasing magnesium content and temperature. Consequently, the rate of increase of the critical strain for the ternary test alloys with respect to temperature is larger with higher magnesium content. For those specimens pre-aged at 273 K, the longer the aging time, the larger the critical strain. Also, the limiting aging time for which the flow instability still exists decreases with increasing magnesium content. Aging should play the role in depleting the quenched-in vacancies and solute atoms.

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I. Introduction

Ternary Al-7 mass% Si-Mg cast alloys with magnesium contents varying from 0.2 to 0.5 mass% have been widely applied in the aerospace and automobile industries. Aluminum alloys containing silicon and magnesium usually exhibit the Portevin-LeChatelier (PL) effect at the temperatures around 220 to 360 K(10)-(16). For A356.2 (Al-7 mass% Si-0.25 mass% Mg) cast alloy which is rapid in natural aging, PL effect can also be observed by suppressing natural aging immediately after solution treatment(11).

When PL effect occurs in substitutional alloys, there exists a strengthening phenomenon that the flow stress is temperature independent instead of the normal softening behavior of decreasing flow stress with increasing temperature(13)(22). Another pronounced characteristic is the onset of flow instability at some critical strain(13)(22). With increasing temperature, the critical strain of many alloys including the Al-Mg binary system(84) and Al-Si-Mg ternary system(89)(90) reveals a U-shaped behavior, that is, it decreases initially and then increases. On the other hand, the critical strain of Al-Si binary alloys decreases asymptotically with temperature(90)(90). Regardless of the diverse high temperature critical strain behavior mentioned above, the critical strain (E) in the low temperature region where it decreases with temperature can be correlated empirically with strain rate (e) and temperature (T) according to the following Arrhenius relation:

\[ \dot{e} \propto \varepsilon_\alpha \exp\left(\frac{-Q}{kT}\right) \quad (1) \]

where \( \alpha \) is a material parameter, \( k \) is the Boltzmann constant and \( Q \) is an apparent activation energy associated with the onset of flow instability.

To rationalize eq. (1), the famous Orowan equation, \( \dot{e} = \rho_v b V \), has been constantly adopted as the basis, where \( \rho_v \), \( b \) and \( V \) are the mobile dislocation density, the Burgers vector and the average dislocation velocity, respectively(89)(90). During the dynamic process, the increase of \( \rho_v \) with increasing strain can be interpreted empirically with a power law relation(90). Meanwhile, the solute-dislocation interaction gives rise to a linear correlation of \( V \) with the diffusion coefficient \( D \) of solute atoms according to either the classical Cottrell-Jaswon model(10) or the aging model proposed by McCormick(90)(90). For substitutional solutes, \( D \) is proportional to \( C_v \exp\left(-Q/kT\right) \), where \( C_v \) is the vacancy concentration and \( Q \) is the activation energy of solute diffusion. As an implication which has been confirmed experimentally(89)(90), the apparent activation energy in the Arrhenius relation of eq. (1) has the physical meaning of the activation energy associated with solute-vacancy site interchange. Also, \( C_v \) increases with strain following an empirical power law relation(89)(90). This power law relation and that of \( \rho_v \) vs. strain mentioned previously are the factors leading to the critical strain exponent, \( \alpha \), of eq. (1).

Besides temperature and strain rate, the aging prior to tension also influences the critical strain of the A356.2 cast alloy(11). Associated with the natural aging effect and the precipitation of MgSi, the critical strain increases with aging time and aging temperature. For the Al-Si-Mg system, the natural aging and precipitation behaviors alter with magnesium content as silicon is usually in excess(12)(16). As an implication, the PL effect of the Al-Si-
Mg system should be influenced by the magnesium content. In the current investigation, Al-7 mass%-Mg cast alloys with magnesium varied from 0.11 to 0.46 mass% were selected to explore the effect of magnesium on the PL effect in these cast alloys. The data on a binary Al-7 mass%Si cast alloy was also used for comparison.

II. Experimental Procedures

Commercial A356.2 ingots, Al-7 mass%Si master alloy and pure magnesium were used as the raw materials to prepare four Al-7 mass%Si-Mg test alloys including Al-7 mass%Si. They were melted by an induction furnace and cast into metal molds at 993 K. The chemical compositions of the four test alloys, as determined by emission spectroscopy, are listed in Table 1. These alloys in the table are designated by their silicon and magnesium concentrations in mass percent.

After casting, tensile specimens with 6 mm diameter and 35 mm length in the gage length section were machined. The tensile specimens were solution treated at 813 K for 12 h, water-quenched to room temperature, and then stored immediately in a mixture of dry ice and ethanol below 208 K to suppress natural aging before conducting a further experiment. As illustrated in the optical metallographs of Fig. 1, the silicon particles have similar shape, size and distribution in all of the alloys. Also, the grain size for all of the alloys is about 400–600 μm.

The tensile tests were divided into two categories. In the first category, the effect of tensile temperature and strain rate were studied by varying the tensile temperature from 223 K to 373 K and the strain rate from $5.7 \times 10^{-4} \text{ s}^{-1}$ to $4.7 \times 10^{-3} \text{ s}^{-1}$. The tests were performed on those solution-treated specimens after holding for 5 min at the given testing temperatures. In the second category, the influence of natural aging was explored in which the solution-treated specimens were pre-aged at 273 K for different aging times from 5 to 1200 min (i.e., 20 h) before tension. The tensile tests were performed at 273 K, which is also the aging temperature, with a strain rate of $5.7 \times 10^{-4} \text{ s}^{-1}$.

III. Results

1. General features of the solution-treated specimens

All the solution-treated specimens exhibit flow instability in which serrated flow appears after some critical strain. Examples are illustrated in Fig. 2. The critical strain of the test alloys is plotted as a function of tensile temperature in Fig. 3 for the strain rate of $5.7 \times 10^{-4} \text{ s}^{-1}$. As those reviewed in Section I, the figure indicates that the critical strain of Al-7Si decreases asymptotically with temperature, while the three Al-7Si-Mg alloys reveal the U-shaped critical strain vs. temperature behavior.

To obtain the activation energy data on the test alloys, the data of Fig. 3 in the low temperature regime are replotted in Fig. 4 by taking the logarithmic critical strain vs. inverse temperature, and the critical strain which increases with strain rate at the temperature of 248 K is plotted logarithmically in Fig. 5. With the slopes of the linear

<table>
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<th>Designation</th>
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<td>Al-7Si-0.46Mg</td>
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Fig. 1 Optical microstructures of the solution-treated cast alloys:
(a) Al-7Si, (b) Al-7Si-0.11Mg, (c) Al-7Si-0.26Mg, (d) Al-7Si-0.46Mg.

Fig. 2 Typical flow curves of the solution-treated Al-7Si-0.26Mg cast alloy showing the serration and the temperature dependence of the critical strain ($\epsilon_c$) at the strain rate of $5.7 \times 10^{-4} \text{ s}^{-1}$.
curves in these figures, the apparent activation energies calculated from the Arrhenius relation of eq. (1) are 33.8 kJ/mol, 51.1 kJ/mol, 59.8 kJ/mol, and 60.8 kJ/mol, respectively, for Al-7Si, Al-7Si-0.11Mg, Al-7Si-0.26Mg and Al-7Si-0.46Mg.

Under the same test condition, as shown in Figs. 3, 4 and 5, the three ternary Al-7Si-Mg cast alloys have a larger critical strain than the binary Al-7Si alloy. Also, there is a tendency that Al-7Si-0.46Mg has the greatest critical strain for each testing condition.

The 0.2% off-set yield stress of the solution-treated specimens is plotted in Fig. 6. Associated with the serrated flow, the yield stress is nearly temperature independent for Al-7Si and Al-7Si-0.11Mg. For the alloys with higher magnesium contents, the yield stress is temperature-independent below about 293 K and increases with temperature.

2. Effect of aging treatment

The results of the aged specimens indicate that the PL effect of the three ternary Al-7Si-Mg test alloys is affected by their prior aging treatment at 273 K, while the PL effect of Al-7Si is not affected. Figure 7 shows the variation of the critical strain with aging time. Except for Al-7Si which reveals an aging-time independent critical strain behavior, the critical strain tends to increase with increasing aging time. Its rate of increase is more pronounced with increasing magnesium content. The upper right end points of the curves of Al-7Si-0.26Mg and Al-7Si-0.46Mg in Fig. 7 also correspond to the limiting
IV. Discussion

1. Solution treated specimens in the low temperature regime

In the low temperature regime where the critical strain can be rationalized by the Arrhenius relation given in eq. (1), the apparent activation energy associated with the onset of serration was obtained in Section III.1 as 33.8 kJ/mol for the solution treated Al-7Si test alloy, which is close to those reported by Niinomi et al. for other Al-Si binary alloys. With the addition of magnesium, the apparent activation energy increases to 51.1 kJ/mol for Al-7Si-0.11Mg, 59.8 kJ/mol for Al-7Si-0.26Mg and 60.8 kJ/mol for Al-7Si-0.46Mg. For the Al-Mg binary alloys, the values of about 53.1 kJ/mol have been reported. Therefore, except for Al-7Si-0.11Mg which has an apparent activation energy close to that of the Al-Mg binary system, the data indicates a larger activation energy for those with higher magnesium content.

As reviewed in Section I, the apparent activation energy has been confirmed experimentally and theoretically as that associated with the diffusion of substitutional solute atoms. The above result that the activation energy increases with increasing magnesium content suggests that an interaction between silicon and magnesium solute atoms exists. The interaction has also been proposed by McCormick in an Al-0.7Mg-0.4Si alloy in which the activation energy value of 59.8 KJ/mol has been reported. Since Mg2Si compound is a stable phase of Al-Si-Mg ternary system, this solute interaction should be attractive and provide an extra energy barrier (i.e., an increase in activation energy) for the diffusion process. As indicated by the higher activation energies, the alloys with higher magnesium contents should have a stronger attractive interaction which in turn retards the formation of dislocation atmosphere. Accordingly, Al-7Si-0.46Mg tends to have the largest critical strain for a given tensile condition in the low temperature range (see Figs. 3, 4 and 5).

2. The effect of aging

For the solution treated specimens deformed in the high temperature range, age hardening occurs at least in Al-7Si-0.26Mg and Al-7Si-0.46Mg. Figure 6 indicates that the yield stress of these two test materials increases with temperature in this temperature range. The figure also shows a larger effect of age hardening with higher magnesium content. As for the 273 K aged specimens, Fig. 8 reveals that the higher the magnesium content and the longer the aging time, the larger the age hardening effect.

The aging characteristic of Al-Mg2Si alloys has been studied with using electrical resistivity measurement. Similar results have been obtained in the aging of Al-7Si-0.3Mg cast alloys. It is believed that clustering of solute atoms and vacancies, i.e., the process of GP zone formation, takes place in the aging process at low temperature. This is often known as pre-precipitation phenomena. Heterogeneous precipitation of Mg2Si at
crystal imperfections occurs at the aging temperature above the GP zone solvus temperature\textsuperscript{16,17}. The GP zone solvus temperature is about 420 K in an Al-Mg-Si alloy with about 0.5 mass% Mg\textsubscript{3}Si\textsuperscript{21}.

Both clustering and precipitation can deplete the quenched-in vacancies and solute atoms, giving rise to the suppression of dislocation atmosphere formation. According to the age hardening results in Figs. 6 and 8, one can deduce that the suppression is more enhanced with increasing magnesium content, tensile temperature and pre-aging time. Figure 3 shows that the rate of increase in critical strain with tensile temperature in the high temperature range is larger with increasing magnesium content. Owing to the same suppression effect, Fig. 7 shows that the critical strain increases with increasing magnesium content and aging time, and that the limiting aging times of Al-7Si-0.26Mg and Al-7Si-0.46Mg within which the flow instability still exists become shorter with increasing magnesium content.

V. Conclusions

The following conclusions are drawn from the above results and discussion:

1. In the low temperature range where the critical strain of the solution-treated alloys decreases with increasing temperature, the apparent activation energy for the onset of flow instability increases with increasing magnesium content, implying that the higher the magnesium content the stronger the solute interaction which impedes the formation of dislocation atmosphere. The implication agrees with the results that the binary Al-7Si test alloy has the smallest critical strain and the solution-treated Al-7Si-0.46Mg with the highest magnesium content tends to have the largest critical strain in this temperature range.

2. For the solution-treated specimens tested in the high temperature range, the rate of increase in critical strain with temperature is larger with increasing magnesium content. For those specimens pre-aged and deformed at 273 K, the higher magnesium content and longer aging time lead to a larger critical strain. The higher magnesium content also leads to a shorter limiting aging time for within which the flow instability still exists.

3. For the solution-treated specimens tested in the high temperature regime, the flow stress data indicate an increasing aging effect with increasing magnesium content and tensile temperature. For those specimens pre-aged at 273 K, the aging effect increases with increasing magnesium content and aging time. With increasing aging effect, the quenched-in vacancies and solute atoms are expected to be more depleted, leading to a larger suppression of dislocation formation. The above statement is consistent with the results of Conclusion (2).

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