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ACOUSTIC EMISSION DURING DEFORMATION OF Al-Li ALLOYS

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Abstract

The relationship between tensile elongation and acoustic emission (AE) detected during compressive deformation of Al-Li and Al-Li-Zr alloys has been investigated for a range of microstructure. For comparison, AE measurements have been carried out for Al-Cu and commercial 7050 alloys. In the polycrystalline binary Al-Li alloys, the most pronounced AE was detected in the underaged condition during the onset of plastic deformation. The AE increased with increasing Li content, attained a maximum emission at 3-4.5% Li and decreased by further addition over the maximum solid solubility of Li in Al. The strong burst AE was detected in the Al-Li single crystal with a multi-slip orientation. In contrast, the AE in the sample with a single slip orientation was appreciably small. The AE in the binary Al-Li alloys was much greater than those in the Al-Cu and 7050 alloys. The addition of 0.1-0.5% Zr to the polycrystalline Al-Li alloy greatly lowered the AE and improved the ductility appreciably. The proposed sources of burst AE in the binary Al-Li alloys during the onset of plastic deformation are the formation of coarse slip bands induced by shearing of L1_2-ordered coherent δ'-particles and the intersection of slip bands with each other and with grain boundaries. The intersection of coarse slip bands and weak grain boundaries are considered to be responsible to the loss of ductility in the binary Al-Li alloys. Transmission electron microscope observations of the interaction between deformation induced dislocations and precipitate particles revealed that the dispersion of fine metastable Al_2Zr particles changed the mode of dislocation glide through the introduction of the Crowan bypass process.

I. Introduction

Aluminium alloys containing lithium harden by the precipitation of δ'-Al_Li phase which is a quasi-equilibrium phase of L1_2 ordered structure. The precipitation of δ'-phase, however, results in decreased ductility. Various mechanisms have been proposed for this reduction of ductility: (a) strain localization due to the planar glide of superlattice dislocations (1)(2), (b) formation of precipitate free zones (PFZ) adjacent to grain boundaries by the preferential precipitation of equilibrium δ-Al Li phase at the grain boundaries(3), (c) segregation of impurity elements at grain boundaries (4)-(8), and (d) dispersion of coarse inclusions (9). Transmission electron microscope investigations of the behaviour of deformation induced dislocations in Al-Li binary alloys as well as 8090 alloy (10)(11) have revealed that the dislocations move as pairs cutting the δ'-particles during the deformation of underaged and peak-aged states. Therefore, the formation of coarse slip bands is considered to be responsible to the low ductility of Al-Li based alloys. However it has been difficult to correlate the magnitude of coarse slip and the extent of the reduction of ductility. Then the influence of ageing conditions and the additional elements on the ductility of Al-Li alloys have not yet adequately been understood.

The purpose of the present work is to measure burst acoustic emission (AE)
which correspond to the avalanche motion of dislocations and crack formation and to evaluate the influence of microstructure on the slip behaviour of Al-Li alloys.

II. Experimental Procedures

The compositions of the alloys used in the present work are given in Table 1. The Al-Li binary and Al-Li-Zr ternary alloys were prepared by induction melting 99.99% Al, 99.8% Li and an Al-5% Zr mother alloy under an Ar atmosphere. A single crystal (SC) of Al-Li binary alloy was grown by the modified Bridgman method in an Ar atmosphere with an alumina powder mold.

The ingots were rolled to sheets and cut to 3mm x 3mm x 4.7mm compressive specimens. Tensile specimens, 12mm in gauge length and 2.4mm x 1mm in cross section, were prepared by a spark cutting machine. The specimens were solution heat treated in glass capsules filled with Ar to prevent oxidation and vaporization of Li, followed by quenching into iced water and aged for various periods. As reference alloys, Al-4% Cu, 7050 and 8090 alloys were also prepared.

The specimens were compression tested at room temperature with an Instron type machine at a nominal strain rate of 3.5x10^-4 s^-1. AE measurements were carried out during the compression test. The elongation to fracture for aged alloys was measured by tensile tests performed at a nominal strain rate of 4.17x10^-3 s^-1. Microstructures and dislocation configurations were investigated by transmission electron microscopy (TEM) using a JEM-1000 high voltage electron microscope in HVEM Laboratory of Kyushu University.

III. Results and Discussion

1. AE of Al-Li binary alloys

Figure 1 shows the stress-strain curves of Al-3% Li alloy at each ageing stage and the corresponding measured AE during compressive deformation. It is clear that the AE is highly sensitive to the ageing condition. The most pronounced burst AE is detected in the underaged state during the onset of plastic deformation. The AE increased with increasing ageing time, and declined for longer time. In the overaged state (e), the burst AE is hardly detected. The stress-strain curves for as-quenched (a), underaged (b), (c) and peak-aged (d) states are serrated and strong AE corresponding to the serration is also detected.

Figure 2 shows the variation of yield stress (0.2% proof stress) and AE of Al-Li binary alloys as a function of aging time at 473K. The AE values in the figure indicate the maximum values detected during onset of plastic deformation of each specimen. The AE is greatest in the 3% Li alloy and decreases by further addition of Li over the maximum solid solubility in Al.

Figure 3 shows the stress-strain curves and AE of Al-2% Li single crystals at each ageing stage during compressive deformation for a multi-slip orientation (a) and for a single-slip orientation (b), respectively. The strong burst AE is detected in the crystal with a multi-slip orientation and in the underaged state. In contrast, the AE with a single-slip orientation is small. These results indicate that the strong AE in the Al-Li alloys is attributable to the intersection of coarse slip bands.

2. AE of reference alloys

The strong burst AE has already been detected in the underaged Al-4% Cu and commercial Al alloys in which shearing of coherent Guinier-Preston zones occurs during deformation (12). The sensitivity of the present system was quite low since the AE transducer was not directly attached to the samples but set to the loading rod to monitor the AE during the whole range of deformation of the brittle alloys.

Table 1. Chemical composition (mass%)

<table>
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<tr>
<th>Alloy</th>
<th>Li</th>
<th>Zr</th>
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<tr>
<td>Al-2Li</td>
<td>1.95</td>
<td></td>
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<tr>
<td>Al-3Li</td>
<td>3.04</td>
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<tr>
<td>Al-4.5Li</td>
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<tr>
<td>Al-6.5Li</td>
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<td></td>
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<td>Al-Li SC</td>
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<tr>
<td>Al-3Li-0.05Zr</td>
<td>2.98</td>
<td>0.047</td>
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<td>Al-3Li-0.1Zr</td>
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<td>0.097</td>
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<tr>
<td>Al-3Li-0.2Zr</td>
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<td>0.21</td>
</tr>
<tr>
<td>Al-3Li-0.5Zr</td>
<td>3.18</td>
<td>0.46</td>
</tr>
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</table>
Fig. 1 The effect of ageing time on the stress-strain curves and AE of Al-3Li alloy.

Fig. 2 (a) 0.2% proof stress and (b) AE of Al-Li alloys aged at 473K.

Fig. 3 The stress-strain curves and AE of Al-2Li single crystals. (a) Multi-slip orientation, (b) single-slip orientation.
Fig. 4 The effect of ageing time on the stress-strain curves and AE of Al-3Li-0.1Zr alloy.

Fig. 5 (a) 0.2% proof stress, (b) elongation and (c) AE of Al-Li-Zr alloys aged at 473K.

Fig. 6 Transmission electron micrographs of Al-3Li-0.1Zr alloy. As-Quenched (a), aged at 473K for 6x10^2 s (b), 1.8x10^3 s (c) and 1.2x10^5 s (d). (a) Bright field image, (b)-(d) 100 dark field images.
The comparison which has been done using the present AE equipment has shown that the burst AE was not detected in these reference alloys within the range of sensitivity of the present system. Therefore it should be clear that the AE in the Al-Li binary alloy is much larger than those in the reference alloys. It should be noted that the AE of peak-aged 8090 alloy was very small.

3. Effect of Zr additions

Figure 4 shows the stress-strain curves and the corresponding AE of Al-3%Li-0.1%Zr alloy. The addition of 0.1%Zr to Al-3%Li alloy greatly lowered the AE as known from Fig. 1 and Fig.4. Figure 5 shows the variation of yield stress (a), elongation (b) and AE (c) of Al-Li-Zr alloy containing various amount of Zr as a function of ageing time at 473K. The elongation of Al-3%Li and Al-3%Li-0.05%Zr alloys decreases as the ageing proceeds and becomes almost zero at peak strength, and can not be restored even at the overaged state. Furthermore, the AE of both alloys during the onset of plastic deformation is very large in the underaged and peak-aged conditions. The addition of 0.1-0.5%Zr to the Al-3%Li alloy depresses the AE and improves the ductility appreciably. The elongation of these alloy is 5-8% even at the peak-aged condition and the ductility slightly restores at the overaged state. The AE of large grained Al-3%Li-0.1%Zr alloy which had been solution treated and aged without rolling after casting was much smaller than that of Al-3%Li binary alloy of which the grain size was almost the same. Therefore the grain refinement is not the main reason of the depression of AE in the Al-Li-Zr alloys. The AE during the onset of plastic deformation and the elongation to fracture are considered to be closely related in the underaged or peak-aged states. However in the overaged state, the depression of AE in the Al-3%Li binary alloy does not improve the ductility. This indicates that only the formation of coarse slip bands is not responsible to the low ductility of the Al-Li alloys.

4. Deformation induced dislocations in the Al-Li-Zr alloys

Figure 6 shows transmission electron micrographs of Al-3%Li-0.1%Zr alloy at different ageing states. As shown in (a), the metastable Al2Zr particles which have relatively large misfit with respect to the matrix lattice precipitate during solution treatment at 823K (13)(14) and can be observed by the Ashby-Brown lobe-type strain contrast in the bright field images. The Al2Zr particles are almost invisible in a dark field image in the as-quenched state. Although the bright field image can not show the precipitation of δ' phase, a 100 dark field image showed easily a uniform dispersion of fine δ'-particles in the as-quenched state. These δ'-particles grow as the ageing proceeds (b, c). Shells of δ' are formed around the Al2Zr particles during ageing and as a result the Al2Zr particles become visible in dark field images as shown in Fig. 6(c) and (d).

Figure 7 shows bright field images of Al-3%Li-0.1%Zr alloy deformed 0.5% in compression after quenching. In (a), fine Al2Zr particles with weak contrast and many dislocation loops with strong contrast in addition to the subgrain networks and strain induced dislocations can be observed. Figure 9(a) reveals that not only the cutting of δ'-particles by superlattice dislocations but also the Orowan bypass process around the Al2Zr particles take place at early stages of ageing. In another region in which the Al2Zr particles are almost absent (b), dislocation dipoles (DD), helical dislocations (HD) and prismatic dislocation loops (PL) are observed, indicating a large difference in the slip mode between these two regions with and without the fine dispersion of Al2Zr.

Figure 8 shows transmission electron micrographs of Al-3%Li-0.1%Zr alloy deformed 3% in compression after ageing. In the early stage of ageing (a), the superlattice dislocations and the Orowan loops around Al2Zr particles are evident. Dislocations forming pairs become wavy as the ageing proceeds and finally single dislocations bypass the particles leaving the Orowan loops around the δ' and δ'/Al2Zr composite particles. The size of Orowan loops are nonuniform indicating the large distribution of particle sizes in this alloy. The resistance to shear is considered to be larger in the Al2Zr particles than in the δ'-particles, dislocations tend to bypass the Al2Zr particles and composite particles and easily form dislocation tangles during deformation (15).
Fig. 7 Bright field images of Al-3Li-0.12r alloy deformed 0.5% in compression at room temperature after quenching.

Fig. 8 Transmission electron micrographs of deformed Al-3Li-0.12r alloy. Aged at 473K for $6 \times 10^3$ s (a), $1.8 \times 10^3$ s (b) and $1.2 \times 10^3$ s. (c). Specimens were deformed 3% in compression at room temperature. (a) Bright field image, (b) and (c) 200 dark field images.
5. Origin of low ductility of Al-Li based alloys

A most possible source of burst AE in the Al-Li binary alloys during the onset of plastic deformation is the avalanche of moving dislocations and the formation of coarse slip bands. This process seems to be responsible to the loss of ductility in the binary alloys. The addition of small amount of Zr disperses fine coherent particles of hard AlZr and introduces the Orowan bypass process to occur, reducing the localized avalanches of dislocations and thus reducing the burst AE. However, only the formation of coarse slip bands can not be responsible to the low ductility of the alloys. Since the fracture of Al-Li alloys is generally intergranular, the intersection of coarse slip bands and week grain boundaries should be taken into account to explain the low ductility of the alloys. The segregation of impurity elements and the formation of PFZ are the proposed mechanisms of weakening of grain boundaries in the Al-Li alloys. Although it is difficult to distinguish these mechanisms from the present investigation alone, the AE measurements seem to be very useful to evaluate the extent of coarse slip in the Al-Li alloys.

IV. Conclusions

1. In the Al-3\% Li binary alloys, the most pronounced AE was detected in the underaged condition during the onset of plastic deformation. The AE of the alloys declined by further ageing and is very small in the overaged state in which dislocations bypass the δ particles. The AE in the single crystal with a multi-slip orientation is greater than that with a single slip orientation. The AE in the Al-Li binary alloy is much greater than that in other Al alloys.

2. The AE detected at the onset of deformation of Al-Li alloys can be interpreted by the avalanche of moving dislocations, the formation of coarse slip bands and their intersections. The AE measurements are useful to evaluate the extent of coarse slip in the Al-Li alloys.

3. The low ductility of Al-Li alloys can not be attributed only to coarse slip. The formation of PFZ and the segregation of impurity elements at the grain boundaries have to be taken into account.

4. The addition of Zr more than 0.1% to the Al-Li alloys greatly reduces the AE. The dispersion of fine metastable AlZr particles introduces the bypass process even at early stage of ageing and suppresses the slip concentration. The addition of Zr to the Al-Li alloys is extremely effective to improve the strength and ductility.

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