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LOW CYCLE FATIGUE AND FATIGUE CRACK GROWTH IN Al-Li, Al-Li-Zr AND 8090 ALLOYS

Y. XIAO and P. BOMPARD

Laboratoire des Matériaux, Ecole Centrale des Arts et Manufactures, F-92295 Châtenay-Malabry Cedex, France

Abstract

The evolution of the properties in low cycle fatigue and fatigue crack growth of binary Al-Li, ternary Al-Li-Zr and 8090 alloys were compared. The respective influences of the main microscopic features of Al-Li alloys were studied. The shearing of δ precipitates induces the formation of intense and heterogeneous slip bands (PSB) and of intergranular cracking. The Al₃Zr precipitates prevent the strong PSB formation in the recrystallized Al-Li-Zr alloy, but the texture enhances brittleness in the unrecrystallized one. Owing to δ', S' and T₄ precipitates, the 8090 alloy exhibited a flow stress almost twice that of other Al-Li alloys, but its fatigue life was reduced by the brittleness of the PFZ at grain boundaries (GB).

All the alloys exhibited a very good crack growth resistance, with AKs threshold higher than 9MPa/m. Very efficient closure effects were due to the crack propagation into PSB or GB. Expressed in terms of AKeff, the resistance of the alloys were comparable to that of the other Al-alloys. The correlation with low cycle fatigue could be achieved through the use of the HRR elastoplastic field and the cyclic stress-strain curve. When related to the cyclic plastic strain ahead of the crack tip, the crack propagation rates could be correlated to the fatigue life in low cycle fatigue.

Introduction

The fatigue properties of the 8090 alloy proved to be good, [1,2,3,4] in spite of strain localization which reduces both low cycle fatigue life and toughness [5,6,7]. The aim of this study is to determine the specific influence of the microstructural features of the 8090 alloy, by comparing binary and ternary alloys behaviours to that of the industrial alloy.

Experimental program

Material

The composition and heat treatments given in table I were chosen in order to study the respective influences of Li in solid solution, of δ' precipitates, of Al₃Zr precipitates and of T₄ and S' precipitates. Besides, a thermomechanical heat treatment was applied to the Al-Li-Zr alloy in order to get a recrystallized structure so as to define the influence of the texture.

Testing procedure

The low cycle fatigue tests were performed on cylindrical specimen under controlled plastic amplitude, at frequencies ranging from 0.05Hz to 0.1Hz. The fatigue crack propagation tests were performed either on RCT (W=45mm, B=3.5mm) or CT (W=50mm, B=10mm) specimens.
Figure 1: Cyclic hardening curves at $\Delta \epsilon_p/2 = 1.5 \times 10^{-3}$

Figure 2: Stress-strain curves

Figure 3: Manson-Coffin curves

Table 1.

<table>
<thead>
<tr>
<th>Designation</th>
<th>alloy</th>
<th>microstructure</th>
<th>ageing</th>
<th>$\sigma_y$ (MPa)</th>
<th>$\sigma_{uts}$ (MPa)</th>
<th>E %</th>
<th>precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSS</td>
<td>Al. 0.7 Li</td>
<td>recrystallized</td>
<td>R.T</td>
<td>32</td>
<td>60</td>
<td>85</td>
<td>5.5 Solution</td>
</tr>
<tr>
<td>B1</td>
<td>Al. 2.5 Li</td>
<td>recrystallized</td>
<td>R.T</td>
<td>75</td>
<td>179</td>
<td>26</td>
<td>$\delta':20-30\text{Å}$</td>
</tr>
<tr>
<td>B2</td>
<td>Al. 2.5 Li</td>
<td>recrystallized</td>
<td>$5^\circ-150^\circ\text{C}$</td>
<td>133</td>
<td>223</td>
<td>14</td>
<td>$\delta':50-80\text{Å}$</td>
</tr>
<tr>
<td>T1</td>
<td>Al. 1.7 Li 0.1 Zr</td>
<td>recrystallized</td>
<td>$5^\circ-150^\circ\text{C}$</td>
<td>98</td>
<td>189</td>
<td>50</td>
<td>$\delta':\text{Al}_2\text{Zr}$</td>
</tr>
<tr>
<td>T2</td>
<td>Al. 1.7 Li 0.1 Zr</td>
<td>recovered</td>
<td>$5^\circ-150^\circ\text{C}$</td>
<td>207</td>
<td>278</td>
<td>16</td>
<td>$\delta':\text{Al}_2\text{Zr}$</td>
</tr>
<tr>
<td>T3</td>
<td>Al. 1.7 Li 0.1 Zr</td>
<td>recovered</td>
<td>$12^\circ-190^\circ\text{C}$</td>
<td>209</td>
<td>278</td>
<td>16</td>
<td>$\delta':\text{Al}_2\text{Zr}$</td>
</tr>
<tr>
<td>8090</td>
<td>2,4 Li 1,3 Cu, 1Mg 0.1 Zr</td>
<td>recovered</td>
<td>$12^\circ-190^\circ\text{C}$</td>
<td>479</td>
<td>547</td>
<td>5</td>
<td>$\delta':\gamma,\text{Al}_2\text{Zr}$</td>
</tr>
</tbody>
</table>
Low cycle fatigue

Experimental results.

The experimental results (fig 1.2.3) show that the recrystallized alloys exhibit during cycling a hardening followed by saturation stage, instead of the recovered alloys which harden and then soften continuously. The cyclic flow stress strongly increases from Al-0.7Li to 8090 but the corresponding fatigue life drastically decreases.

a) Binary alloys

The cyclic flow stress of the precipitation hardened Al-2.5Li alloy (δ~80 Å) is 150 MPa greater than that of the solid solution, but the fatigue life is nearly 10 to 20 times shorter. The fracture behaviour changes from ductile, with striations, to brittle, with a fracture path localized in slip bands or grain boundaries (fig 4a, 5a). The dislocation structure of the solid solution is cellular, [5] and consist of planar pile ups in the (111) planes in the aged Al-2.5Li alloy (fig 4b, 5b), due to the shearing of δ' precipitates [8,9,10]. This induces a strain localization in persistent slip bands (PSB) and stress concentrations in these bands and at their intersections with grain boundaries (GB), leading to an early crack initiation in PSB or GB (fig 6).

b) Al-Li-Zr alloy

The recrystallized Al-1.7Li-Zr alloy is very comparable to the binary Al-Li alloy, the plastic strain being nevertheless more homogeneous (effect of Al3Zr) and the PSB and GB less brittle (lower Li %). On the contrary, the sharp texture of the unrecrystallized state induces a strain localization on only one or two slip systems in the whole specimen [12]. This leads to a macroscopic strain softening and induces a brittle fracture in the PSB thus formed.

c) 8090 alloy.

The hardening effect of the δ',T1, and S' precipitates lead to a cyclic flow stress almost twice that of the ternary alloy at the same state, and the fatigue life is strongly reduced. The non shearable S' precipitates allow plastic strain homogenization at the subgrain scale, [11,12,13] through the activation of several slip systems in the same subgrain (fig 6b). Nevertheless, this does not prevent a brittle fracture in PSB or GB because of the existence of the texture and of δ' precipitate free zones at GB. Besides, the plastic strain remains very heterogeneous at a macroscale, due to the low cumulative plastic strain to fracture (fig 6a).

Fatigue crack propagation

Experimental results.

The figures 7 and 8 show that, related to ΔK as well as to ΔKeff, the crack growth rate decreases from Al-0.7Li to 8090 alloy. It must be noticed that this effect is quite the opposite of that observed in low cycle fatigue.

Discussion

All the alloys studied have a very high threshold ΔKs ranging from 6 to 9MPa/m, except for the solid solution whose threshold is lower (3MPa/m) and comparable to that of conventional alloys. The fatigue crack growth rates are also very low, except for the unrecrystallized Al-Li-Zr alloy. This high fatigue strength is a consequence of the shearing of δ' precipitates in PSB, which leads to an irregular crystallographic path and so to a very high closure effect on the crack lips. This is confirmed by the values of Kopening (fig 9) which remain constant for medium ΔK (above ΔKs) and decrease for higher ΔK, because new slip systems are activated in front of the crack tip, leading to a decrease of the lips roughness.
**Figure 4:** Al-0.7Li (BSS).

a: fracture surface with striations. SEM.
b: cellular dislocation structure. TEM. [5].

**Figure 5:** Aged Al-2.5Li (B2).

a: brittle fracture in PSB and GB. SEM.
b: planar slip bands. TEM.

**Figure 6:** 8090 alloy (IN).

a: fracture in PSB and GB. SEM.
b: slip bands in three directions. TEM.
Figure 7.

Figure 8.

Figure 10: Unrecrystallized Al-Li-Zr alloy (T3): crack path.

Figure 9: Al-2.5Li (B2). a: crack path. b: fracture surface. c: Kopen-ΔK.

Figure 11: 8090 alloy (IN): crack path.
When related to \( \Delta K \) effective, the threshold of all the alloys is the same (3MPa\( \sqrt{m} \)), and the fatigue curves are brought together, except for the unrecrystallized Al-Li-Zr alloy. It can be noticed however that, for precipitation hardened alloys, large \( \delta' \) precipitates allow a better strength than finer \( \delta' \) or than the solid solution.

The sharp texture of the recovered Al-Li-Zr induces the formation of long slip bands which develop through many grains. The opening normal stress applied to the slip band is not then relaxed by plastic deformation on secondary slip systems and remains very high, leading to the crack propagation into a single macro slip band on distances as large as a few millimeters (fig 10). The fatigue crack growth rates thus remain higher than for the other alloys.

This unfavorable effect of the texture is not observed in the 8090 alloy because, as it was observed in low cycle fatigue, several slip systems are activated in the same subgrain: the normal stress is thus relaxed and the crack direction changes at each GB (fig 11).

Relation between low cycle fatigue and fatigue crack propagation rates.

It can be assumed that a given point ahead of the crack tip is progressively damaged by plastic cycling as the crack propagates. So the amplitude of the cyclic plastic strains in front of the crack tip should give, together with the Manson Coffin curves, the crack growth rates.

A precise description of the cyclic plastic zone being very difficult in the case of unhomogeneous strains, we qualitatively used HRR strain field [14,15] with the cyclic strain hardening exponent \( n \) of the stress-strain law: \( \varepsilon_p = \varepsilon_0 (\sigma/\sigma_0)^{2n} \), and \( \sigma_0 \) the cyclic yield stress:

\[
\Delta \varepsilon_p = \alpha \left( \frac{\Delta K}{\sigma_0} \right)^{1+n}
\]

where \( \Delta K \) is the effective \( K \) amplitude.

We can thus express the crack growth rates as function of the cyclic plastic strain at a given distance in front of the crack tip which, in such a qualitative analysis, remains arbitrary. The figure 12 shows an excellent agreement (except for unrecrystallized Al-Li-Zr) between the fatigue crack growth strength and the low cycle fatigue strength: submitted to the same \( \Delta \varepsilon_p \), the crack growth rate is directly related to the fatigue life. In the case of the unrecrystallized Al-Li-Zr alloy, the single crystal type behaviour in front of the crack tip leads to higher crack growth rates: the behaviour of a small element is no more comparable to that of a polycrystalline specimen.

![Figure 12](image-url)
Conclusion

-The shearing of $\delta'$ precipitates induces strain localization in PSB which results in brittle fracture and decrease of the low cycle fatigue life. However the crack growth behaviour is strongly enhanced by strong closure effects due to the roughness of the crack lips.

-The sharp texture developed in Al-Li-Zr alloys decreases the number of active slip band and allows the propagation of the crack on one slip bands through many grains: both low cycle fatigue and fatigue crack growth strengths are lowered.

-In the industrial alloy, the $S'$ precipitates induce a strain homogenization in the subgrain by activating several slip systems. This leads, in spite of the texture, to a high crack growth strength. Nevertheless the low cycle fatigue life remains very short, because the very high values of the cyclic flow stress induce a premature initiation of crack in PSB or GB.

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