FATIGUE CRACK PROPAGATION BEHAVIOUR OF THE Al-Li ALLOY 8090 COMPARED TO 2024
M. Peters, V. Bachmann, K. Welpmann

To cite this version:

HAL Id: jpa-00226624
https://hal.archives-ouvertes.fr/jpa-00226624
Submitted on 1 Jan 1987

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
FATIGUE CRACK PROPAGATION BEHAVIOUR OF THE Al-Li ALLOY 8090 COMPAORED TO 2024

M. PETERS, V. BACHMANN and K. WELPMANN

DFVLR, Institut für Werkstoff-Forschung, D-5000 Köln 90, F.R.G.

ABSTRACT

The fatigue crack propagation behaviour of the Al-Li alloy 8090 was evaluated on 25mm plate material and compared to the conventional high strength Al alloy 2024. Tests were performed in air and 3.5% NaCl solution at R-ratios of 0.1 and 0.7. The results revealed that for most conditions the Al-Li alloy was equivalent or better than the conventional Al alloy. The superior behaviour of 8090 was shown to be primarily a result of crack closure.

INTRODUCTION

Aircraft parts which are exposed to fatigue loads are designed according to a damage tolerance philosophy. This favours material which tends to be most tolerant to existing (micro-) defects like cracks or flaws. Laboratory tests on fracture toughness and fatigue crack growth yield the necessary information about the resistance to propagation of cracks under static and cyclic loading conditions, respectively. Since the new class of Li-containing Al alloys are primarily developed for aircraft application the knowledge about their damage tolerance performance is essential. In an attempt to better understand the fatigue crack propagation behaviour of Al-Li alloys investigations were performed on 25mm plate material of the first of the new generation of low-density Al alloys, 8090. Comparison tests were run on two tempers of 2024, T851 and T351, the latter being the conventional damage tolerant Al alloy.

EXPERIMENTAL

The two alloys investigated were supplied in the form of 25mm plate material. 8090 had been solution heat treated, stretched and aged to a T651 temper by Alcan International Ltd. The composition in wt.-% was Al-2.42Li-1.24Cu-0.60Mg-0.12Zr-0.12Fe-0.05Si-0.05Ti. The 2024 plate was received in the naturally aged T351 temper. Half of the plate was aged to T851 (Table 1).

Tensile tests in longitudinal (L) and transverse (T) direction were performed on 3mm thick flat specimens with a gauge length of 75mm and a width of 12.5mm at an initial strain rate of 4.4·10⁻⁴ 1/s. An extensometer was used to determine the elastic modulus, E, and the 0.2% yield strength.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Stretch</th>
<th>Aging Treatment</th>
<th>Test Direction</th>
<th>E [GPa]</th>
<th>YS [MPa]</th>
<th>TS [MPa]</th>
<th>EI [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8090-T651</td>
<td>X</td>
<td>16h 190°C</td>
<td>L</td>
<td>78.9</td>
<td>448</td>
<td>502</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T</td>
<td>79.8</td>
<td>417</td>
<td>521</td>
<td>6.2</td>
</tr>
<tr>
<td>2024-T351</td>
<td>X</td>
<td>--</td>
<td>L</td>
<td>73.6</td>
<td>365</td>
<td>464</td>
<td>17.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T</td>
<td>73.9</td>
<td>332</td>
<td>475</td>
<td>11.5</td>
</tr>
<tr>
<td>2024-T851</td>
<td>X</td>
<td>9h 190°C</td>
<td>L</td>
<td>73.8</td>
<td>486</td>
<td>510</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T</td>
<td>74.0</td>
<td>473</td>
<td>509</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 1 Heat treatments and tensile properties (average values over the plate thickness) of the alloy conditions investigated.
Fatigue crack propagation was measured on a servohydraulic testing system using 12.5mm thick compact tension specimens in LT orientation. Since the Al-Li alloy revealed a strength profile in through-thickness direction [1] specimens were machined out of the center of the plate. Sinusoidal wave forms were applied at R-ratios of 0.1 and 0.7. The frequency was kept constant at 30Hz. Tests were performed at ambient temperatures in laboratory air and in a 3.5% NaCl solution. Crack growth was monitored by a DC potential drop technique [2]. Fractographic investigations of the fracture surfaces were performed by scanning electron microscopy (SEM).

RESULTS AND DISCUSSION

Microstructure and Tensile Properties

Fig. 1 shows the microstructure of the alloys investigated. Both materials exhibit a pancake grain structure which is typical for high strength Al alloys. The Al-Li alloy has, however, a finer and unrecrystallized grain structure and a lower volume fraction of big constituent particles, which are mostly aligned along grain boundaries (Fig. 1a). Furthermore, transmission electron microscopy revealed [3,4] that the T651 temper contained a high volume fraction of very fine, homogeneously distributed δ′ and plate-like S′ particles in the matrix and the equilibrium δ phase at the grain boundaries along with precipitate-free zones and very fine A12Zr particles which are known to inhibit recrystallization. The influence the microstructure has on the fracture behaviour is discussed elsewhere [3,5].

Whenever the fatigue behaviour of Al-Li alloys is compared to that of conventional high strength Al alloys, one has to make sure to find the appropriate comparison alloys, meaning primarily that those alloys should reveal a similar strength level. The results of the tensile tests show that the above assumption is substantially fulfilled since the yield and tensile strength levels of 8090-T651 fall between those generated for 2024-T351 and T851 (Table 1).

Fatigue Crack Propagation Behaviour

Although Al-Li alloys are only available since a couple of years, their fatigue crack propagation behaviour has been already the subject of extensive investigations [3, 4, 6 to 14]. Most authors find that Li-containing alloys exhibit an excellent resistance to fatigue crack propagation, at least for low to intermediate growth rates. The results of the present investigation on 25mm plate material of 8090-T651, 2024-T351 and T851 (Fig. 2) support these findings. In laboratory air and at a R-ratio of 0.1 fatigue crack growth properties of the Al-Li alloy are superior to 2024-T351 and T851 (Fig. 2a). This is especially pronounced for intermediate growth rates (3 to 8x10⁻⁴ mm/cycle) where the curves for 8090 showed a distinct plateau, i.e., an extended region with nearly constant crack growth rate. Here, cracks propagated partly more than an order of magnitude slower than the conventional alloy tempers. At the high R-ratio of 0.7, however, the differences between the Li-free and Li-containing alloys decrease, although a slightly better behaviour was still observed for 8090, especially when compared to 2024-T851 (Fig. 2a).

Figure 1 Optical micrographs of the L-S plane of 8090 (a) and 2024 (b).
The crack growth curves generated for the three alloy conditions in 3.5% NaCl solution are plotted in Fig. 2b. It is obvious that at low R-ratio 8090-T651 and 2024-T351 show a much better crack propagation behaviour than 2024-T851, with the Al-Li alloy being mostly superior. The differences between the three alloy conditions disappear, however, for the tests performed at R = 0.7.

If one considers that 2024-T351 is the conventional damage tolerant high strength Al alloy, i.e., showing the best resistance to propagating cracks, the fatigue crack growth behaviour of 8090 has to be rated excellent. This in particular since the present alloy's T651 temper is not specifically designed for damage tolerance. These observations are in agreement with the majority of the da/dN-ΔK curves published in the literature.

Figure 2 Fatigue crack growth curves of 8090-T651, 2024-T351 and 2024-T851 tested in air (a) and 3.5% NaCl solution (b) at R = 0.1 and 0.7 (LT orientation).
The reasons for the outstanding performance of Al-Li alloys are manifold. It is argued that part of the improved crack growth resistance can be attributed to the higher elastic modulus \([6, 8]\). Although there is no doubt that increased stiffness results in reduced crack opening displacement and therefore lower growth rates, the authors, here, believe that the higher elastic modulus does not play a prime role in the explanation of the improved crack growth resistance of Al-Li alloys. Otherwise the superiority of 8090 at \(R=0.1\) in the present investigation should not diminish at the high \(R\)-ratio (Fig. 2). The dominant effects are thought to come from what is referred to as microstructural influences. Here, the coherent, ordered and shearable \(\delta'\) precipitates play a key role in that they lead to inhomogeneous slip, high plastic strain accumulation and a strong crystallographically oriented crack path. This tendency is intensified by a strong crystallographic texture \([11]\). Both, the coherent nature of the hardening phase \(\delta'\) as well as the strong preferred crystallographic texture are very typical features of Li-containing Al-alloys \([5, 16-18]\). They are believed to cause effects like increased slip reversibility - an idea originally proposed for an Fe-based superalloy \([19]\) - crack deflection \([20]\) or branching, crack closure due to mode II displacements or surface roughness \([21]\), which are thought to be the reasons for the superior fatigue crack propagation behaviour of 8090 in the present investigation.

Looking closer to the present results in Fig. 2, it is obvious that nearly over the entire \(\Delta K\) range 8090 is superior over the 2024 tempers for \(R=0.1\) in both, laboratory air and 3.5% NaCl solution. For the high \(R\)-ratio of 0.7, however, the superiority of the Li-containing alloy nearly disappears for both environments. The most likely effect which leads to such a strong retardation at low \(R\)-ratio and which diminishes with increasing \(R\)-ratio is crack closure. So far, it is not totally clear what kind of closure - oxide-, roughness- or plasticity-induced - is active. It is, however, suggested that roughness-induced closure plays the dominant role since a) plasticity-induced closure is only important under plane stress conditions, i.e., at high \(\Delta K\) values and/or for thin cross sections and b) oxide-induced closure was found to play a minor role in Al-Li alloys, due to only very thin oxide layers formed on the fracture surface \([22]\). The roughness of the fracture surface, which is a result of intense inhomogeneous slip and texture, can easily be recognized from the SEM fractographs of 8090 tested in air at \(R=0.1\) (Fig. 3). The pictures indicate that the roughness is less pronounced in the threshold region (Fig. 3b) than at intermediate growth rates (Fig. 3c). This can substantially explain the retardation in crack growth in the plateau area. Why the roughness increases from the threshold to the plateau area is not fully understood. A correlation with the microstructure is, however, obvious: at the transition from threshold to medium crack growth rates for \(R=0.1\) the plastic zone size measures about 10 to 20 \(\mu m\) which corresponds roughly to the thickness of the pancake-shaped grains \([3]\).

Although roughness-induced closure can account for a good portion of the improved fatigue crack growth resistance of 8090 at low \(R\)-ratio, the outstanding crack retardation in the plateau area caused us to look for additional explanations. Such plateau areas, which are even more pronounced in TL orientation \([3, 4]\), seem to be quite typical for Al-Li alloys since they were also observed for 2090 \([15]\) and 2091 \([14]\). Macroscopic inspection of the fatigued 8090 CT specimens revealed a large dark fracture area (Fig. 3a) for intermediate growth rates of about \(3\times 10^{-6}\) to \(3\times 10^{-5}\) mm/cycle, which corresponds directly to the plateau (Fig. 2a). Such dark areas were also found on the high \(R\)-ratio 8090 specimens, but much less pronounced \([3]\). They were, however, not detected for 2024. This means that the dark areas only appeared in conjunction with a plateau. Similar observations were also made by 't Hart and Schra \([13]\). SEM investigations revealed that in the dark region (Fig. 3a) extended portions of the fracture surface were densely covered with fine spherical deposits as shown in Fig. 3d. They are thought to be the product of extensive fretting processes. This assumption is supported by the observation that the fracture surface in the plateau area is considerably rougher than in the threshold area (compare Figs. 3c and b), thus making fretting processes more likely.

In conclusion, this means that the excellent fatigue crack propagation behaviour at intermediate crack growth rates is thought to be primarily a result of crack closure due to surface roughness and fretting debris deposits.
Figure 3 Fractography of a fatigued and fractured CT specimen ($R = 0.1$, air, LT-orientation) of 8090-T651. The macrograph (a) reveals areas of low (1), medium (2) and high fatigue crack propagation rates (3) and final fracture (4). SEM pictures are taken from areas 1 (b), 2 (c and d), and 3 (e).
The area of the fracture surface which corresponds to the area beyond the plateau appears again light in the macrograph (Fig. 3a, region 3). Here, no deposits were found although severe roughness was still observed (Fig. 3e). The reason why no fretting deposits were detected might be due to the fact that - as a result of the drastically increased growth rate (Fig. 2a) - the number of cycles per unit is much reduced and simultaneously the propensity for fretting.

Since at high R-ratio the Al-Li alloy still shows partly a superior propagation behaviour in air over the conventional alloy, closure effects cannot account alone for the excellent fatigue crack growth behaviour of Al-Li alloys. Other possible explanations include crack deflection and crack branching. Both lead to reduced stress intensities at the crack tip(s) thus decreasing the fatigue crack growth rate. In the present investigation a specifically nice example for crack branching was observed for 8090. Fig. 4 shows the polished surface of a fatigued CT specimen with secondary cracks measuring more than 10mm.

Another interesting observation made in the present study for 8090-T651 and 2024-T351 is the fact that the threshold for fatigue crack growth at R = 0.1 is higher in the more aggressive 3.5%NaCl solution than in air (compare Figs. 2a and b). Similar observations had also been made earlier for 7475 [23] and 7075 [24]. It is believed that such a behaviour is due to another closure effect caused by corrosion debris on the fracture surface, especially since this effect disappears at the high R-ratio. To get experimental evidence on this statement, a CT specimen of 8090-T651 was fatigued at R = 0.1 in air to near-threshold growth rates. Then the crack tip was flooded with aqueous 3.5% NaCl solution, while the specimen was continuously cycled. As expected from the da/dn-ΔK curves, the crack growth rate decelerated and finally stopped in the sodium chloride solution. During the whole procedure the load/displacement of the specimen was continuously monitored by back face strain gages as well as clip gages which were mounted on the front of the CT specimen. Both measuring techniques indicated independently that the crack tip opening load increased by about 10% after the change of the environment (Fig. 5). Therefore crack closure effects caused by corrosion debris which deposits on the fracture surface and thus reduces the effective ΔK give the explanation for higher threshold values measured in the corrosive environment than in air. This statement is underlined by the high R-ratio tests where such observations were not made due to the lack of closure.
Figure 5: Increase of crack tip opening load of 8090-T651 (R=0.1, LT orientation) at threshold growth rates during the change of environment from air to 3.5% NaCl solution.

ACKNOWLEDGMENTS

The authors would like to thank Dr. R. Grimes of Alcan International Ltd., Banbury, UK, and W. Zink of MBB, Bremen, FRG for kindly providing the 8090 and 2024 plate material, respectively.

REFERENCES