Fatigue of aluminium alloy 2024-T351 in humid and dry air

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Reversed bending fatigue tests conducted on specimens of aluminium alloy 2024-T351 in dry and humid air at stress levels of 248, 276, 290, 317 and 359 MPa showed that at low stress amplitude humid air reduces the fatigue life by as much as 21%. Micro-hardness tests showed that the reduction in fatigue life is primarily attributed to localized hydrogen-induced over-ageing. SEM analysis and microhardness data were combined with past studies to propose a mechanism for environmentally induced fatigue in aluminium alloy 2024-T351 over a wide range of stress levels.

1. Introduction

Although opinions differ as to the cause, there is general agreement that the fatigue life of high-strength aluminium alloys is reduced in humid environments [1-12]. The greatest amount of research has been done on the environmental effects on the fatigue crack propagation rate [1-4, 8-11]. Studies have shown that water vapour has a more pronounced effect on the fatigue crack propagation rate when the stress amplitude is low [1, 9]. It has also been determined that water vapour appears to be the primary factor in accelerating the fatigue crack propagation rate, because the rate was observed to be the same in wet air, wet argon and wet oxygen [4]. Locally induced hydrogen over-ageing may be a contributing factor to the acceleration of the propagation rate and hence the reduction of the fatigue life at low stress levels [6].

From the studies reviewed during this research it is evident that controversy exists between the results and theories of past investigations [8, 12]. There are data which support the theory that humidity plays an insignificant role in the reduction of the fatigue life of 2024-T351 [7, 12] and data that support the opposite view [2, 4-6].

This research investigated the combined effects of stress level and water vapour density on the fatigue life of 2024-T351 extruded bar stock in reversed bending. The results of this research provide information regarding the relationship between the stress level and the environment. Scanning electron microscopy (SEM) and microhardness data were combined with past studies to propose a mechanism for environmentally induced fatigue in aluminium alloy 2024-T351 over a wide range of stress levels.

2. Experimental procedure

Cylindrical reversed bending fatigue specimens (50 in all) were machined from five bars of 0.50 in. (~1.25 cm) diameter extruded commercial 2024-T351. The average mechanical properties for the material were \( \sigma_u = 490 \text{ MPa} \) and \( \sigma_y = 331 \text{ MPa} \). Ten specimens were machined for each fatigue stress level (248, 276, 290, 317 and 359 MPa). The cycling was conducted in an environmentally controlled chamber designed according to ASTM B117. Five specimens from each stress level were cycled in desiccated air at a relative humidity less than 45%. The remaining five specimens were cycled in a mist environment with a relative humidity greater than 95%.

SEM examination of the fracture surface was performed using an Amray model AMR1000 electron microscope. Microhardness was investigated in rejoined fatigue-fractured specimens over the range 40 to 1100 μm from the fracture surface. The measurements were made on a Wilson-Fukon microhardness tester using a 1000 g load.

3. Results

The fatigue results are presented in Fig. 1. At the lowest stress level the humid environment was found to cause at least a 21% reduction in the fatigue life of the 2024-T351 specimens. When the stress level reached 317 MPa the effect of the environment was substantially reduced. At the final stress level of 359 MPa the effects of the environment can be considered negligible and the fatigue lives in dry air and wet air can be considered to be equal.

SEM fractographs of possible crack initiation sites, topography of fatigue surfaces and overload regions were made to support the findings of the experimental data. In general, the fatigue fracture zones of the high cycle–low stress specimens cycled in dry air exhibited more ductile characteristics (microvoid coalescence in combination with pronounced striations) than did the specimens cycled at the same stress in wet air. Figs 2 and 3 show the fatigue fracture regions for the 248 MPa dry and wet air specimens. Fig. 3 (for the specimen in wet air) shows an eroded surface with secondary cracking and corrosion deposits. These features are clearly not visible in Fig. 2 (for the
specimen in dry air). At 359 MPa (Figs 4 and 5) the fatigue fractured surface of the wet specimen is very similar to that of the dry specimen, confirming the fact that the stress level was the controlling variable.

Figs 6 and 7 present the data from the microhardness tests. It is clear that the greatest difference in hardness occurred between the 248 MPa dry and wet specimens, at the closest distance to the crack. These results were probably due to hydrogen-enhanced over-ageing [6]. Also evident in these results is the fact that for all specimens, as the distance from the crack increases the hardness becomes more uniform regardless of the environment. This result is easily understood as well, because any environmentally induced over-ageing would occur in the immediate vicinity of the crack where hydrogen is readily diffused into the metal [6].

4. Discussion

From the data presented in this study it is obvious that at the lower stress levels investigated, high humidity does have a deleterious effect on the fatigue life of 2024-T351. This observation is shared by other researchers who have studied the 2xxx series alloys [9-11]. A complete review of the literature to date does find several authors in conflict with the results presented here [4, 8, 12]. In an effort to understand the mechanism of fatigue failure for 2024-T351 in a humid environment these differences need to be addressed.

In the papers suggesting that humidity has no effect on the fatigue life [4, 8, 12] it can be seen that the specimens were all cycled at stress levels less than those studied in this research. Comparing this fact with the current research suggests that there might exist two transition stress levels. Above the upper transition level the environment has little effect on the fatigue life as the exposure time is not long enough for the corrosion effect to become apparent. Below the lower transition level, a humid environment might have a beneficial effect on the fatigue life of the 2xxx series alloys. The existence of a lower transition stress level was evident in the work by Wilson et al. [12] on 2024-T351 in reversed torsion. Their S–N curve (Fig. 8 of [12]), clearly shows a transition stress level about 17 x 10^3 p.s.i. (117 MPa). A transition stress level near this value was also observed in other work [5, 6]. What may be occurring at these low stress levels is that the oxide layer build-up present on the crack surface may be interfering with the closure of the crack, thereby reducing the stress intensity at the crack tip and in turn lengthening the fatigue life. This hypothesis is supported, in part, by Vasudevan and Suresh [10].

A mechanism for the fatigue failure of 2024-T351, at any stress level, in a humid environment may now be presented. In an aggressive environment crack initiation is exposure-time dependent. In order for electrochemically induced pitting and hydrogen softening to