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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%. Mirco-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 fatique 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 $\sigma_u = 490$ MPa and $\sigma_y = 331$ 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–Tukon 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

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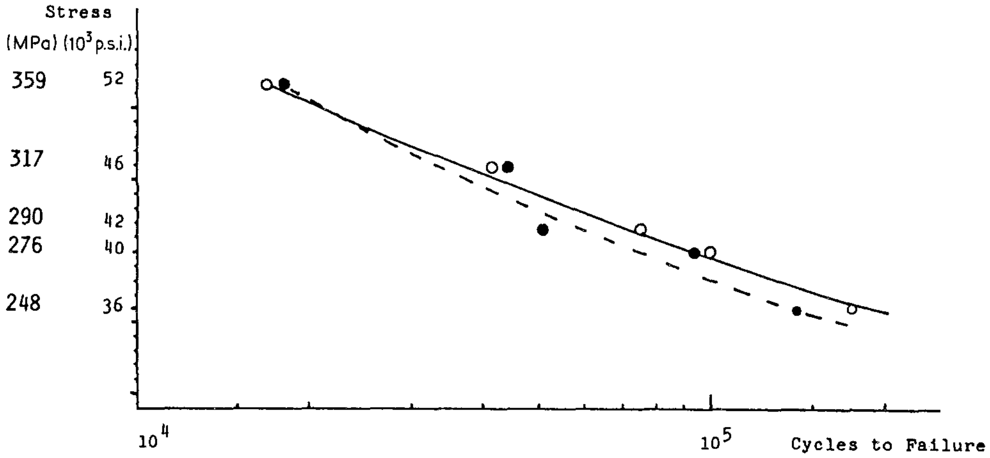

Figure 1 Fatigue *S–N* curves for 2024-T351 specimens cycled in reversed bending in (○) dry and (●) humid air.

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 × 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

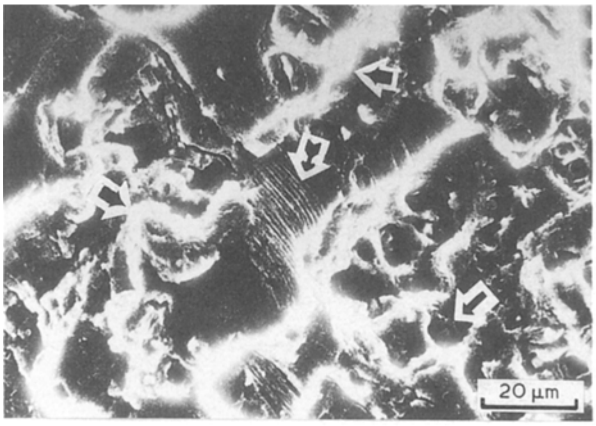

Figure 2 SEM fractograph of 248 MPa dry air specimen. Arrows indicate striation, dimple and tear ridge.

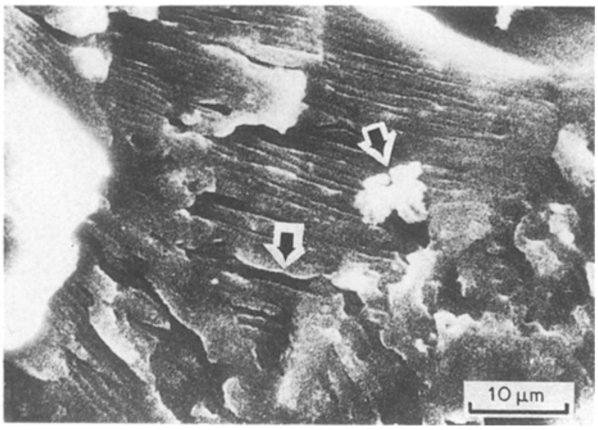

Figure 3 SEM fractograph of 248 MPa humid air specimen. Arrows indicate secondary crack and a possible corrosion deposit.

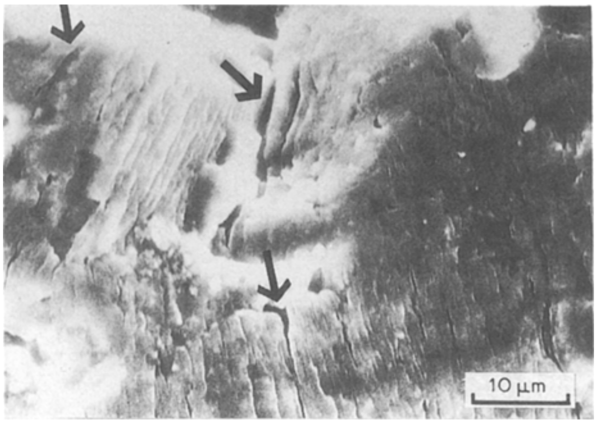

Figure 4 SEM fractograph of 359 MPa dry air specimen. Arrows indicate secondary fatigue cracks.

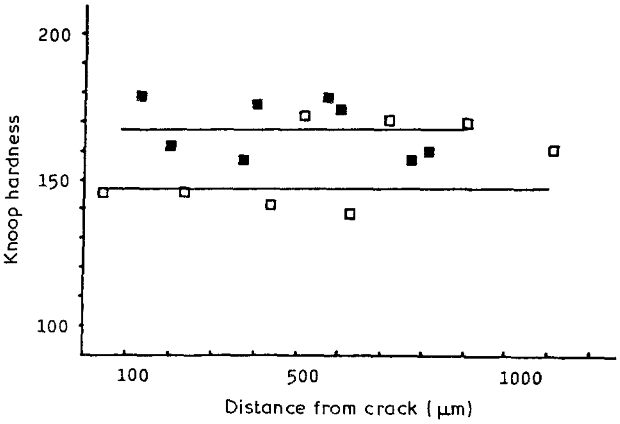

Figure 6 Variation of Knoop hardness with distance from fatigue crack for 359 MPa specimens, in (□) desiccated and (■) humid air.

occur and influence crack initiation, the specimen must be cycled for some time in the adverse environment. Exposure time translates directly to stress level. Above the upper transition stress level, the exposure time is not long enough for deleterious effects to occur. Below the upper transition level electrochemical pitting will occur at numerous places and indicate that numerous crack initiation sites would be present. This is observed in this study as shown in Fig. 8. As the crack forms, the freshly exposed material, as well as the crack tip, are coated and temporarily passivated by a layer of aluminium oxide. Hydrogen formed during this reaction escapes or is trapped under the oxide layer. The trapped hydrogen has sufficient time to react and be absorbed into material ahead of the crack tip. This softens the material making it vulnerable to rapid crack advancement. Therefore, the fatigue life is reduced. As the oxide cracks and exposes new material, pieces of oxide may "flake off" and land on the crack surface. If the crack opening is large enough (at a stress level above the lower transition level) the oxide particles are of little significance. If the crack opening is small, as is the case below the lower transition stress level, the oxide particles may interfere with crack closure on the compression cycle. Because the crack resharpens itself on this portion of the cycle, oxide particle interference would tend to lower the stress intensity at the crack tip and lower the crack propagation rate. The net result of this process just discussed may be an increase in the fatigue life of the specimen.

At hand now is a concise mechanism describing the effects of humidity on the fatigue life of 2024-T351 at any stress level. At high stress levels it was found that the stress level dictates the fatigue life with insufficient time allowed for detrimental environmental effects. At moderate stress levels the fatigue life in humid air was found to be exposure-time dependent. Exposure time was directly related to stress level; the lower the stress level the longer the exposure time. The fatigue life of 2024-T351 cycled in humid air was found to be the most affected when the exposure time was the longest. Finally, as has just been discussed in the preceding paragraphs, there may exist a lower transition stress level (which for 2024-T351 appears to be approximately 103 to 117 MPa) below which the corrosion product tends to slow the propagation of the crack, and the fatigue life in humid air may actually be longer than the fatigue life in dry air.

5. Conclusions

The data presented in this research can be compiled to form the following conclusions.

1. The humidity effects on the fatigue life of 2024-T351 depends on the stress level. At high stress levels the effects were found to be insignificant. At intermediate stress levels humid air was found to have a significant negative effect on the fatigue life of 2024-T351.

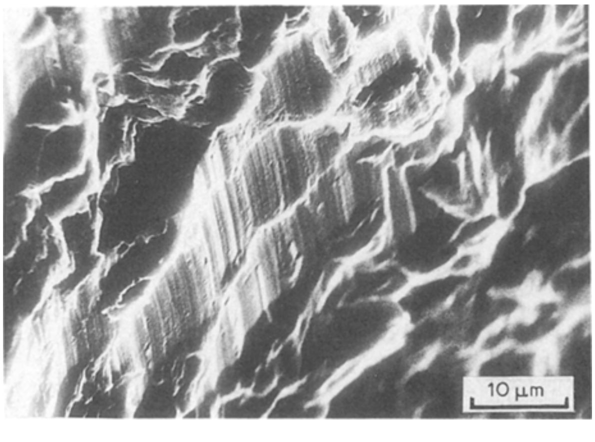

Figure 5 SEM fractograph of 359 MPa humid air specimen.

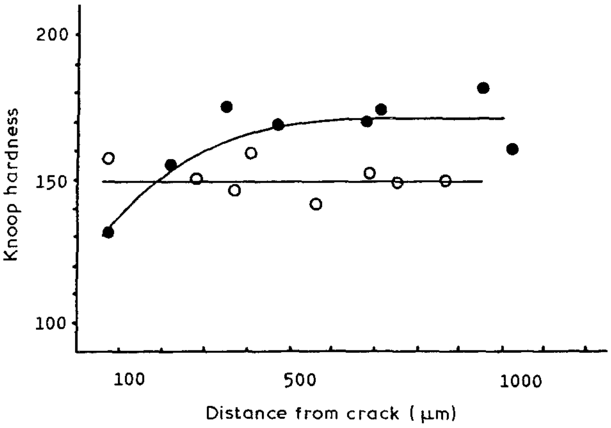

Figure 7 Variation of Knoop hardness with distance from fatigue crack for 248 MPa specimens, in (○) desiccated and (●) humid air.

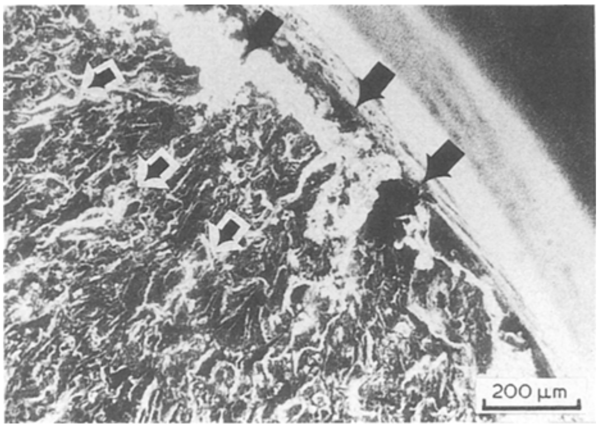

Figure 8 SEM fractograph of 248 MPa humid air specimen. Arrows indicate fatigue initiation sites and fatigue propagation paths.

2. The scanning electron microscope analysis of the fracture surfaces showed similarities between the humid and dry air specimens cycled at high stress levels, confirming the insignificant effect of humidity on fatigue life at high stress levels.

3. The scanning electron microscope analysis of the fracture surfaces showed distinct differences between the humid and dry air specimens cycled at intermediate stress levels.

4. The Knoop microhardness data showed localized over-ageing at the crack tip in the 248 MPa humid air specimen. However, no softening at the crack tip was found in the 359 MPa humid air specimens indicating that the environmental effects were minimal.

5. Discrepencies between this research and the research of others may be explained by the interference of oxide particles with crack closure below the lower transition stress level (approximately 103 to 117 MPa), where the fatigue lives of 2024-T351 specimens cycled in humid air are greater than the fatigue lives of specimens cycled in dry air.

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