Effects of Aging and Environment on Fatigue Crack Growth in Precipitation Hardened Al-Cu-Mg

Daoming Li and Richard P. Gangloff

Artificial aging degrades the fatigue crack growth (FCG) resistance of heat treatable aluminum alloys, particularly in the near-threshold regime. Consequently, applications of aluminum alloys in tension-dominated structures that require fatigue damage tolerance are limited to the naturally aged T3 temper. Degraded FCG resistance compromises the benefit from higher strength by artificial aging. While studies on the effect of aging on FCG in 2xxx series aluminum alloys are limited, mechanisms of fatigue damage and crack growth primarily based on investigations of 7xxx-series alloys involve interactive, competitive and highly localized (at the crack-tip) processes including (a) cyclic deformation structure and plastic strain accumulation, (b) environmental interaction, (c) roughness and corrosion product-induced closure, and (d) crack deflection and path tortuosity. FCG in aluminum alloys is enhanced by exposure to moist air, likely due to production of embrittling H by crack-tip reaction of water vapor with aluminum. Studies recognized the importance of environment, but have not included systematic studies of FCG in varying tempers of the same alloy exposed to different-controlled environments. Ultra-high vacuum conditions are particularly important in this regard given the reactivity of aluminum.

The objective of the present research is to understand the degradation of intrinsic FCG resistance of 2xxx-series alloys due to microstructural changes during artificial aging. AA2024-T351 was aged at 190°C for various times from 0.2 to 48 h to study the FCG behavior as a function of aging microstructure. The FCG tests were performed in a computer-controlled and automated servohydraulic machine using compact tension (CT) specimens. Constant $K_{\text{max}}$ loading mode was selected to minimize extrinsic crack closure. Major environment conditions included water vapor-saturated air (or wet air) and high vacuum at room temperature. Wet air was provided by clamp-sealing the CT specimen in a channeled Plexiglas chamber, with filter-purified air passing consecutively through two beakers filled with distilled water, giving a relative humidity (RH) of 85 – 98% (Fig. 1a). For vacuum FCG experiments, the CT specimen was mounted in a metal-bellows and copper-gasket sealed stainless steel chamber with an external servohydraulic actuator (Fig. 1b). The vacuum level for testing was established and maintained with an oil-free cryogenic pumping system to achieve a residual pressure at and below 0.3 µPa.

The microstructure of AA2024-T351 evolved on a fine scale during the early stage of artificial aging. $S'$ (Al$_2$CuMg) precipitates were resolved clearly by TEM for specimens aged for 4 h and longer at 190°C (Fig. 2), whereas atom clustering and vacancy to dislocation loop rearrangement were believed to be the
dominant microstructure changes in naturally aged and short time ($\leq 2$ to $4$ h) artificially aged AA2024-T351.

FCG results indicate that water vapor enhances crack growth rate for a wide range of $\Delta K$ and $R$ values, as compared with the corresponding behavior in high vacuum (Fig. 3). The microstructural effect on $da/dN$ is dramatic for low $\Delta K$ and vacuum, but also present for higher $\Delta K$ and wet air conditions. For tests in high vacuum, where the environmental effect is minimized, the FCG curves in Fig. 3 represent intrinsic fatigue resistance for respective microstructures. The FCG behavior in high vacuum (Fig. 3) can be divided into three groups in terms of aging: (1) Low-$da/dN$ for $0-1$ h aged alloys having the highest FCG resistance, (2) High-$da/dN$ for $\geq 4$ h aged alloys having the lowest FCG resistance, and (3) Transition Group for ~ $2$ h aged alloys behaving as a transition between Ggroups (1) and (3). This division of FCG characterization is more evident in the low $\Delta K$ region than in the high $\Delta K$ region, as depicted in Fig. 4. As such, naturally aged and short-time artificially aged alloys demonstrate a higher resistance to FCG, probably correlating with the presence of Cu-rich clusters, but without zones or $S'$ precipitates. Initial degradation in FCG resistance with artificial aging might be due to either changing cluster or vacancy-loop dislocation characteristics or precipitation of fine zones and perhaps $S'$ not resolvable by TEM. Increased artificial aging to peak strength further degrades FCG resistance, which is unaffected or slightly improved by overaging.

Fractographic observations by SEM indicate that the fatigue fracture surface in the low $\Delta K$ regime is characterized by intersecting facets for natural aged and short term ($\leq 1$ h) artificially aged alloys (Fig. 5, left) whereas this feature disappears for alloys aged 4 h and longer (Fig. 5, right). This latter fractographic feature is not significantly different from that observed in high $\Delta K$ regions, as well as in wet air environment. As microstructural effects on FCG should be governed by intrinsic plasticity-based crack tip damage, further investigations are under way to provide experimental and analytical evidence to understand specific underlying micromechanism(s) for the observed FCG resistance degradation in association with microstructural evolution.

Acknowledgment __ This research was enabled by a grant from Alcoa Technical Center. The TEM work performed in the Center is gratefully acknowledged.

Related publications:


Fig. 1. FCG test environment and loading system build-up for wet air (left) and high vacuum (right) conditions.

Fig. 2. TEM of AA2024-T351 aged at 190°C for 4 h: (left) \{100\}-SAED pattern, and (right) corresponding dark field image.
Fig. 3. FCG behavior at constant $K_{\text{max}}$ tested in wet air (85–98% RH) or high vacuum (0.1–0.3µPa) for AA2024-T351 aged for various time at 190°C.

Fig. 4. FCG rate (da/dN) as a function of 190°C-aging time for AA2024-T351 stressed in high vacuum (0.1–0.3µPa) at selected $\Delta K$ levels.

Fig. 5. SEM fractographs of low $\Delta K$ (~4-5 MPa.m$^{1/2}$) FCG in high vacuum (0.1–0.3µPa) for AA2024-T351 aged at 190°C for 0.2 h (left) and 4 h (right).