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A study of nucleation and fatigue behavior of an aerospace aluminum alloy 2024-T3

Ali Merati *

National Research Council of Canada, Institute for Aerospace Research, Montreal Road, M-13, Ottawa, Ont., Canada K1A 0R6

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Abstract

The fatigue failure process exploits the weakest links (discontinuities) within the test material, which act as nucleation sites for crack origins. This paper summarizes the results of a study on the 2024-T3 aluminum alloys in different forms (clad and unclad), loading directions, thickness and environment. Microstructural features such as particles, grain size, and clad layer, which dominate fatigue performance have been identified, classified, and statistically characterized. Two distinct mechanisms were found to be responsible for crack nucleation. Constituent particles were found to be the crack origins in unclad sheets. There was almost no evidence of multiple nucleation sites in the unclad material. The fatigue crack origins in clad sheets, however, were located at the surface of the clad. No constituent particles were found to be associated with crack nucleation. Multi-nucleation sites were observed in the clad material.

Keywords: Fatigue life; Nucleation; Aluminum alloy 2024-T3; Discontinuities; Constituent particles; Cladding

1. Introduction

The fatigue failure process exploits the weakest links (discontinuities) within the test material, which act as nucleation sites for crack origins. To develop a material-based and reliable life prediction methodology, there is a need to demonstrate direct link between microstructural features and fatigue performance. At present, there is no generally accepted methodology for analyzing the interactive effects of corrosion and fatigue and predicting the resulting residual strength and structural life of corroded aircraft components.

National Research Council of Canada (NRC), Institute for Aerospace Research (IAR), has participated in a collaborative research and development project with the objective of producing a reliable corrosion/fatigue life prediction methodology. The program was called the Corrosion Fatigue Structural Demonstration (CFSD) Program. The purpose of the program was to develop and demonstrate tools and methods for including corrosion in the durability and damage tolerance analysis of aircraft structures [1]. The method uses a subset of the Initial Discontinuity State (IDS) in manufactured material, as the initial condition for crack growth analysis. The original computation of the IDS fatigue subset is based on test coupon fatigue results only. In addition to test results, there is a need for fractographic data to identify the origin of the fatigue.

Recent publications [2–5] have shown that a direct link exists between the IDS (mainly constituent particles in unclad aluminum alloy sheet) and sites where fatigue cracks originate. The presence of a clad layer at the surface could also accelerate the nucleation process [6]. However, confirmation and demonstration of the applicability of the IDS concept to fatigue life assessment are needed.

The Equivalent Initial Flaw Size (EIFS) durability analysis method has been used on USAF aircraft [7]. In this method, crack sizes found after the teardown of a test specimen or retired aircraft are extrapolated back to a hypothetical EIFS. The EIFS method is generally only valid for a specific structural detail, loading and stress condition, and failure mode. Since a set of EIFS

* Tel.: +1-613-993-7385; fax: +1-613-990-7444.
E-mail address: ali.merati@nrc.ca (A. Merati).

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models is needed for each pre-corrosion severity, even the modeling of pre-corrosion and fatigue with this method would be costly. The fatigue modeling strategy pursued recently has been to find a materials-based model with the flexibility to simulate various mechanisms of corrosion fatigue interactions, component geometries, stress conditions, etc. Ideally a holistic life prediction approach should start with an IDS distribution, which is unique and independent of growth parameter for a material with a given surface finish. This approach uses what is termed IDS to describe the initial analysis condition of the materials. The desired flexibility is being achieved by finding a combination of initial discontinuity size and basic crack growth model that is characteristic of the material alone, and does not depend on the geometry of the structural detail.

To meet the objective of the study, a three-stage approach was taken: (i) microstructural analysis, (ii) fatigue testing, and (iii) post-fracture analysis. The work resulted in the identification of the main microstructural features responsible for crack nucleation under the test conditions used as well as the measurement of IDS data and fatigue test data. More details of test procedures and results are presented in Ref. [8].

2. Materials and approach

Test specimens and coupons for this study were taken from purchased new stocks and from recently retired aircraft fuselage panels. The new stocks of aluminum alloy were cut from 1.6 mm (0.063″) sheets (thin) and 4 mm (0.160″) sheets (thick) of unclad 2024-T3. The used material, 1.6 mm sheet 2024-T3 with both sides clad, had been removed from a C-130 fuselage.

Using standard procedures, metallographic sections were prepared and scanning electron microscopy (SEM) techniques were used in the as-polished condition to measure the size and the distribution of the constituent particles.

Standard axial force controlled fatigue tests were conducted under constant-amplitude loading, and stress ratios were maintained at +0.1. An ASTM E466 [9] standard smooth specimen with continuous radius between ends (hourglass) was used. The cyclic frequency was 10 Hz. The fatigue tests were conducted in two controlled relative humidity (RH) environments of greater than 98% and less than 2% RH. Clad specimens were machined in both directions, so that they could be fatigue tested in the transverse direction as well as longitudinal direction. SEM fractography was performed on all failed fatigue coupons to identify the nucleation sites and to determine which groups of discontinuities are pertinent to fatigue crack formation. In addition to physical characterization of the observable particles, some limited chemical characterizations of observable particles were also performed using Energy Dispersive X-ray (EDX) analysis.

3. Results

The results of microstructural analysis, fatigue testing, and fractographic analysis are presented in the following sections.

3.1. Microstructural analysis

Based on a previous study [2], analysis in this work focused on characterizing the constituent particles and their distributions, and on identifying the subset of particles that were associated with crack nucleation. Constituent particles in each plane (ST, LT, and LS) were examined. The two letter abbreviations used, as per ASTM specifications, refer to the rolling plane (LT), transverse plane (ST), and longitudinal plane (LS). Images of a 2 mm^2 area of each plane in each material were surveyed and analyzed. A limited number of sections were also etched to reveal other observable microstructure features, such as grain structure and clad layer. These features were recorded using optical microscopy. Typical appearances of the as-polished and etched microstructure of the aluminum alloy unclad and clad 2024-T3 studied are shown in Fig. 1a. The microstructure of clad 2024-T3 is revealed in Fig. 1b. The interior clad layer was found intact with a thickness of 60 μm. The exterior clad layer was found to have a rougher surface with an approximate thickness between 20 and 35 μm. The exterior clad layer could have been exposed to conditions such as corrosion, washing, and paint stripping.

The main focus of the microstructural analysis was to measure the dimensional characteristics of the constituent particles. The distributions of large particles throughout the width and thickness of the sheets were investigated. Although the results of the width and thickness analysis did not reveal any strong trend, it was found that the average area of particles is slightly larger in the center-width and mid-thickness. A slightly higher concentration of particles on the outer edge of the specimen thickness is shown in Fig. 2a. As the minimum particle filter size increases, it is revealed that the largest particles are in and near the mid-thickness of the plate (as seen in Fig. 2d). It was also found that the thick material had more large (>200 μm^2) particles than the thin material. In addition, the particles in the thin material had a higher population density. Total numbers of approximately 41,000 particles were analyzed.

A two-parameter Weibull analysis was performed on each direction and each plane (Fig. 3a). A typical linear plot for distribution of area of particles in the ST plane of new 2024-T3 thin is shown in Fig. 3b. The