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Microstructurally small fatigue crack growth in thin, aluminum-alloy, pressure vessel liner

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Abstract

Motivation to decrease weight and cost of composite-overwrapped pressure vessels used in space exploration leads to designs that challenge the current qualification standards and methods for predicting fatigue life of the structures. Namely, as thickness of the metallic, overwrapped liners is reduced (potentially to tens of grains through-thickness), plastic deformation extends to the liner bounds, and linear elastic fracture parameters become invalid for fatigue crack growth characterization. In this case, fatigue crack growth is likely governed by microstructural features of the material. Life predictions should ultimately reflect this microstructural dependence. In this work, we design a study that involves both experimental and computational modeling aspects to gain three-dimensional perspective of the microstructural features influencing fatigue crack growth in a thin aluminum alloy reminiscent of a metallic liner material. High-energy X-ray diffraction microscopy is explored as a method for characterizing microstructural morphology, including crystallographic orientations, in a volume of material containing a microstructurally small fatigue crack. Initial work involves a feasibility study of the material form (rolled sheet versus actual liner material) to be used in the proposed experimental study. An outlook on future work of the study is provided.

Keywords: low-cycle fatigue; pressure vessel; crack nucleation; X-ray diffraction microscopy; tomography; finite element modeling.

1. Introduction

Composite-overwrapped pressure vessels (COPVs) are used to store and transport highly pressurized fluids for various aerospace applications. The composite overwrap provides strength while the metallic liner (typically aluminum 6061-T6, an Al-Mg-Si alloy) prevents contained fluids from permeating the
overwrap. Historically, liner thicknesses have been on the order of 1 mm or greater, and NASA has used a safe-life approach for qualifying them [1]. In the safe-life approach, a single COPV liner selected from a batch of liners is subjected to representative lifetimes of pressurization-depressurization cycles. If the liner does not fail during the qualification test, the batch is approved for use. While the safe-life approach has been accepted for COPV qualification to-date, it provides no understanding of where, why, or at what rate fatigue cracks initiate and propagate within the liners. As NASA seeks to reduce weight and cost of the COPVs by designing “ultrathin” liners (<0.75 mm thickness), an understanding of the mechanisms governing fatigue crack initiation and subsequent propagation in the liners is crucial.

Numerous findings indicate that fatigue cracking in ultrathin 6061-T6 COPV liners is inherently three-dimensional, low-cycle in nature, and microstructurally small. First, fatigue cracks in 6061-T6 tend to nucleate at Fe-bearing surface particles [2-4] (see Fig 1). Such surface cracks potentially propagate through the thickness of the liners. These cracks are three-dimensional in nature, as the rate of through-thickness propagation, which can vary along the crack front, is more critical than the rate of propagation on the liner surface. Second, for ultrathin 6061-T6 as compared to thicker 6061-T6, widespread yielding and increased fatigue crack growth rates have been reported [1], both of which are characteristics of high-strain, low-cycle fatigue [5]. Unlike low-strain, high-cycle fatigue applications, where total fatigue life is often consumed by crack nucleation, nucleation generally occurs early in low-cycle fatigue, and crack propagation dominates total low-cycle fatigue life. This behavior was observed in 6061-T6 [6]. Third, based on (1) the size of fatigue cracks relative to grain sizes and liner thickness and (2) observed variability in local fatigue crack growth rates [1], early fatigue crack propagation in ultrathin 6061-T6 liners is considered to be “microstructurally small” [5]. Unfortunately, no work to-date has sufficiently accounted for all these attributes in addressing where, why, and at what rate microstructurally small fatigue cracks (MSFCs) nucleate and subsequently propagate within COPV liners.

Fig. 1. SEM micrographs showing manufacturing-induced flaws at Al-Fe-Si particles in aluminum 6061-T6 rolled sheet. The flaws serve as potential sites for MSFC nucleation.

The purpose of this ongoing work is to provide NASA with a fundamental, three-dimensional understanding of mechanisms governing MSFC growth in ultrathin, 6061-T6, COPV liners subject to low-cycle fatigue conditions. In particular, the proposed research method combines non-destructive, three-dimensional, experimental techniques with post-mortem fractography and advanced computational tools to relate MSFC nucleation and propagation to surrounding morphology, slip, and stress fields. Results could yield a quantitative assessment of the least and most influential parameters affecting MSFC nucleation and propagation along with possible recommendations for enhancing liner processing methods. Additionally, the combined experimental and numerical method is general such that others can follow it for different material systems and applications.

The following sections describe a proposed experimental and numerical modeling study of MSFC nucleation and propagation in 6061-T6 subject to low-cycle fatigue. Preliminary material characterization results are provided, and an outlook of future work is described.
2. Method

Detailed experimental observations coupled with advanced computational simulations will provide an understanding of mechanisms that drive MSFC nucleation and growth and will enable the development of accurate fatigue life prediction models for ultrathin, 6061-T6, COPV liners. A similar overall approach was described in [7,8], where various MSFC stages were simulated for an aluminum alloy 7075-T651 aircraft component. In that work, electron backscattered diffraction (EBSD) measurements of crystallographic texture in the vicinity of MSFCs were incorporated into detailed finite element (FE) models with crystal plasticity. The FE models, however, were limited to two-dimensional surface data. In the case of ultrathin COPV liners, it cannot safely be assumed that MSFC behavior observed on the surface is the same as that through the thickness. In fact, Ferrié et al. observed that growth rates for a semi-elliptical surface crack are higher at the “deepest” point along the crack front than at the specimen surface for a fine-grained Al-Li alloy [9]. Based on this type of observation, it is especially important to understand fatigue crack growth behavior along the entire crack front in ultrathin COPV liners. Therefore, fully three-dimensional observations should be made to inform the three-dimensional FE models.

2.1. Experimental method

The three-dimensional, experimental data of interest for this work include the geometry of MSFC surfaces at various stages of loading and bulk grain morphology, including crystallographic orientations, surrounding the MSFCs. To obtain this information, a combination of tomography, high-energy X-ray diffraction microscopy (HEDM), and fractography will be employed following low-cycle fatigue tests on samples of 6061-T6. Typically, low-cycle fatigue applications are characterized by component failure within 50,000 cycles [10] and by sufficiently large loading ranges to cause significant plastic deformation prior to failure [5]. Detailed descriptions of test methods to emulate typical low-cycle fatigue behavior can be found in [10].

In this work, a low-cycle fatigue experiment is adapted to facilitate in-situ, microscopic observation of fatigue crack nucleation and subsequent propagation on the sample surface. This is accomplished by a specimen design with a flat gauge section (rectangular cross-section) rather than a round gauge section. Feltner and Mitchell described various specimen designs for low-cycle fatigue tests, including a design with a flat sample surface [11]. An overview of the experimental procedure, including specimen preparation, is shown in Fig 2 and is described next.

As-received 6061-T6 material is first cut into rectangular samples then reduced at mid-height to <0.65 mm thickness using a wire EDM and polishing procedure. Each sample is then fatigue loaded and simultaneously monitored for indications of MSFC nucleation and subsequent propagation. Once one or more fatigue cracks are identified and tracked to a certain amount of propagation, wire EDM is again used to machine around observed MSFCs. Final sample dimensions (Fig 2c) are meant to accommodate the constraints imposed by X-ray tomography and HEDM. As part of an initial sizing study, prototype specimens were machined to the dimensions shown in Fig 2c. One of the prototypes is shown in Fig 2d.

Following fatigue testing, samples are characterized using X-ray tomography and HEDM. Three-dimensional mapping of material attenuation coefficients using X-ray tomography can enable reconstruction of crack surfaces in bulk material [9,12,13]. In [12], Ludwig et al. found that the surface geometry and propagation behavior of a short fatigue crack in an aluminum alloy was much more complex in the bulk of the material than at the observable sample surface. The source of observed complexity was related to crack interactions with the material microstructure. While X-ray tomography is able to reveal the shape of fatigue crack surfaces in three dimensions, it cannot distinguish, in its classic form, the crystallographic orientations of similar-phase grains surrounding the crack surface.
X-ray diffraction microscopy—HEDM, in particular—can be used to nondestructively reveal crystallographic information in bulk material, including individual grain orientations in polycrystalline material [14,15,16,17]. The method has been used for measuring deformation of individual grains in a polycrystalline material during cyclic loading (e.g. [18]); for gathering statistical, microstructural information for polycrystalline materials (e.g. [19]); and for determining elastic moduli of individual grains in a polycrystalline material (e.g. [20]). A very similar method, “diffraction contrast tomography”, was used in [21] to relate stress corrosion cracking to grain boundary orientations (i.e., misorientation between neighboring grains) in an austenitic stainless steel. To-date, very little work has been done using HEDM for three-dimensional studies of microstructurally small fatigue cracking.

An ideal MSFC growth experiment would involve in-situ monitoring of evolving fatigue crack surfaces with (potentially evolving) grain morphology mapping. However, due to current instrumentation limitations, accessibility constraints, and the fact that exact locations for MSFC nucleation cannot be determined a priori, this ideal approach is currently infeasible. Thus, post-mortem fractography can be used after HEDM to extract additional information from fatigue crack surfaces.

The three-dimensional, numerical information of interest in this work includes various parameters (e.g., stress and slip fields, crack tip displacements) along the crack front at different stages of loading, all of which cannot readily be determined from the current experimental procedure. For the complex, three-dimensional MSFC behavior inherent in this work, accurate determination of such parameters requires high-fidelity numerical models that correctly describe the polycrystalline structure of the material and the material response to loading. The former can be accomplished by post-processing the HEDM data and constructing FE models of the replicated microstructure. Information collected from tomographic images and post-mortem fractography can also facilitate geometric replication of the crack surface.

The material behavior in the 6061-T6 will be modeled using crystal plasticity. One reason for this is because the stress fields in the material near MSFCs are likely to be heterogeneous due to crystallographic texture and presence of second-phase particles. Also, orientation of slip planes with respect to the local crack plane can influence trajectory of MSFC growth [22]. Thus, it is important to incorporate a material model that inherently accounts for slip activity. Additionally, a number of other complex global material behaviors, including the Bauschinger effect and cyclic hardening or softening, can be reproduced using crystal plasticity models [23]. The procedure for calibrating a crystal plasticity model is briefly described in [24,25]. The objective in the calibration procedure is to find material parameters that minimize error between simulated and experimental global responses, where the simulation accounts for actual microstructural characteristics of the material used in experiment.
While the numerical modeling aspect of this study remains largely incomplete, the reader is referred to [8] for a description of numerical modeling work very similar to the intended work here.

3. Preliminary results and future work

An initial step of this study involved characterizing as-received 6061-T6 rolled sheet material to determine its feasibility of use for the described research objective. Two measures of feasibility were considered, namely: (1) microstructural similarity of the rolled sheet material to the actual COPV liner and (2) adequacy of the grain structure in the rolled sheet material for HEDM resolution capabilities.

Samples of the rolled sheet were polished and characterized using EBSD. Orientation imaging micrographs (OIMs) of the material are shown in Fig 3. Average grain sizes in the rolled sheet are \( \approx 23 \, \mu \text{m} \) in the rolling direction (RD), \( \approx 22 \, \mu \text{m} \) in the transverse direction (TD), and \( \approx 11 \, \mu \text{m} \) in the short or normal direction (ND). In the COPV liners, grain sizes are \( \approx 30 \, \mu \text{m} \) in all directions. Further, assuming the spatial resolution available for HEDM ranges from 1 \( \mu \text{m} \) to 4 \( \mu \text{m} \), a 30 \( \mu \text{m} \) grain size is more amenable to the technique than a 10 \( \mu \text{m} \) grain size. Thus, 6061-T6 rolled sheet material is deemed infeasible for this study.

Subsequent work will focus on using actual material from a cylindrical COPV liner provided by NASA. The same experimental and numerical procedure described above will be employed. However, because the as-received material is cylindrical in form, the specimens will be cut in the longitudinal direction and milled flat to achieve the sample geometry depicted in Fig 2a.

Completion of this work will have significant implications for the design and qualification procedure that NASA uses for the ultrathin COPV liners. Additionally, the general method can be used for three-dimensional MSFC studies of other materials and applications.

Fig. 3. Inverse pole figure maps of 6061-T6 rolled sheet in the RD-TD plane (left) and in the RD-ND plane (right).

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