DOT/FAA/TC-24/15

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

DARWIN® Roadmap for Cold Dwell Fatigue

June 2024

Final report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

1. Report No. DOT/FAA/TC-24/15	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DARWIN® Roadmap for Cold Dwell Fatigue		5. Report Date June 2024
		6. Performing Organization Code
7. Author(s) James C. Sobotka, Michael P. Enright, R. Craig McClung		8. Performing Organization Report No. 18.28050
9. Performing Organization Name and Address Southwest Research Institute® 6220 Culebra Road San Antonio, TX 78238-5166		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. FA8650-23-C-5203
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Policy & Standards Division Engine & Propulsion Section, AIR-625	U.S. Air Force Research Lab AFRL/RXNMB 2230 10th Street B655 RM 020 Wright-Patterson AFB, OH 45433	13. Type of Report and Period Covered Final Report, January 2022-August 2022
		14. Sponsoring Agency Code AIR-625 and AFRL/RXNMB

15. Supplementary Notes

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16. Abstract

Cold dwell fatigue (CDF) is a time-dependent process in near-alpha titanium alloys at temperatures below 300°C that involves metal degradation in the presence of creep to produce cracking on low-energy fracture facets in preferentially oriented, hard-alpha grains. It can cause significant reductions in fatigue life, and experience has shown that it can potentially result in catastrophic rotor failure. Well established methods have not been developed to incorporate this failure mode into assessments of component life and fracture risk management.

The US Air Force Research Lab (AFRL) tasked Southwest Research Institute® (SwRI®) to investigate the feasibility of integrating a crack growth approach into DARWIN® to assess the impact of CDF on life and risk assessments. This effort involved critical review of the model proposed by AFRL, practical considerations of its implementation, and discussions with third parties to provide industry perspectives. As a result of this effort, this report was written to describe the AFRL methodology and outlines key improvements to DARWIN needed to support this effort. The proposed approach relies on the model proposed by Pilchak and co-workers that treats CDF as a crack growth issue amenable to damage tolerance (DT) approaches.

SwRI anticipates limited issues adding this capability into DARWIN, though it would require significant effort to design, implement, verify, integrate, and document the new approach. New DARWIN capabilities would build on earlier capabilities to assess lives and risk for cracks under cyclic fatigue crack growth and time-dependent crack growth mechanisms. SwRI recognizes several challenges associated with obtaining the data needed to support the proposed assessment capability. These concerns are noted in the roadmap along with an overview of the anticipated modifications to DARWIN needed to support these calculations.

17. Key Words Cold dwell fatigue; Damage tolerance; DARWIN; Microtextured region; Fatigue crack growth; Time-dependent crack growth; Air France flight AF066; Titanium; Probabilistic damage tolerance	18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 37	19. Security Classif. (of this report) Unclassified

Acknowledgements

We wish to acknowledge the contributions of other personnel to the content of this document throughout various meetings, emails, and other exchanges. At AFRL, we acknowledge Pat Golden, Reji John, and Andy Rosenberger. At P&W, we acknowledge Adam Pilchak, Vasisht Venkatesh, and Mike McClure.

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Acronyms

Acronym	Definition
AFRL	Air Force Research Laboratory
CDF	cold dwell fatigue
DARWIN®	Design Assessment of Reliability With INspection
DDT	deterministic damage tolerance
DT	damage tolerance
EBSD	electron backscatter diffraction
EC-MTR	equivalent critical microtextured region
ECEC-MTR	equivalent critical-exceedance curve microtextured region
FAA	Federal Aviation Administration
FCG	Fatigue crack growth
FIB	Focused ion beam
GUI	graphical user interface
MC	Monte Carlo
MTR	microtextured region
P&W	Pratt & Whitney
PDT	probabilistic damage tolerance
SCG	small crack growth
SwRI®	Southwest Research Institute®
TDCG	time-dependent crack growth
TMF	thermal-mechanical fatigue

Executive summary

Cold dwell fatigue (CDF) is a time-dependent process in near-alpha titanium alloys at temperatures below 300°C that involves metal degradation in the presence of creep to produce cracking on low-energy fracture (e.g., cleavage) facets in preferentially oriented, hard-alpha grains. It can cause significant reductions in fatigue life, and experience has shown that it can potentially result in catastrophic rotor failure. Well-established methods have not been developed to incorporate this failure mode into assessments of component life and fracture risk management.

Treating the CDF mechanism has become more urgent due to the recent incident during Air France flight AF066 on September 30, 2017. During this flight from Paris (France) to Los Angeles (USA), CDF in Ti-6Al-4V contributed to an engine failure that forced an emergency landing. One contributing factor was the (common) assumption that the CDF mechanism was absent in titanium alloys with a residual amount of the beta-phase, e.g., Ti-6Al-4V. Consequently, some recent engines have been manufactured using Ti-6Al-4V without considerations for CDF, which would have led to design or usage modifications.

AFRL tasked SwRI to investigate the feasibility of integrating a crack growth approach into DARWIN to assess the impact of CDF on life and risk assessments. This effort involved a critical review of the model proposed by AFRL, practical considerations of its implementation, and discussions with third parties to provide industry perspectives. As a result of this effort, this report was written to describe the AFRL methodology and outline key improvements to DARWIN that are needed to support this effort. The proposed approach relies on the model proposed by Pilchak and co-workers that treats CDF as a crack growth issue amenable to damage tolerance (DT) approaches. DT almost always treats anomalies as cracks from the initial state. This conservative approach ignores the long lives associated with crack formation and captures the rare event where an anomaly slips through the inspection process. However, these rare events drive fatigue processes in the scenarios that limit lives.

The AFRL approach considers three crack growth mechanisms: cyclic fatigue crack growth (FCG), cyclic small crack growth (SCG), and time-dependent crack growth (TDCG). FCG mechanisms act under cyclic loading conditions to increase the crack size. FCG processes are decoupled from the time-duration. Contributions from FCG and SCG mechanisms involve the standard models (Paris and El Haddad, respectively) and are identical within and without the MTRs that drive CDF. TDCG processes within the micro-textured region (MTR) represent the novel characteristic of the AFRL approach. MTRs support a complicated slip transfer process

between strong and weak slip systems that ultimately underlie the CDF process. Here, TDCG is treated as a Paris-like process dependent on the maximum value of the stress-intensity factor that is corrected to consider SCG. TDCG requires a maximum threshold stress to trigger the TDCG mechanism, and the TDCG process saturates after some dwell time limit is reached. In this framework, the key inputs are the initial crack size, the size of the Equivalent Critical MTR (EC-MTR), and the material properties highlighted to compute crack growth. The material properties (particularly the TDCG properties) require specialized testing to determine their values and (if desired) their variability for risk assessments.

CDF is only active within critical MTRs, which are MTRs aligned with the local stress to promote crack growth. Critical MTRs are spread throughout the material, and a crack may grow through many critical MTRs before encountering a limit state. AFRL proposed a conservative approach. Here, an EC-MTR merges all MTRs that could be encountered by a crack into a single region (the EC-MTR) with an equivalent area. The EC-MTR is centered at the crack and accelerates crack growth under dwell loadings. Crack tips feature TDCG if the crack tips remain within the EC-MTR.

A PDT approach can be taken to determine risk from CDF processes. An exceedance curve of EC-MTR (the ECEC-MTRs), crack growth rate variability, and other random variables drive the risk calculations performed by the PDT approach. A Monte Carlo sampling process samples these variables and determines crack growth increments. In the proposed PDT approach, the initial crack size is taken as a deterministic value set based on the prime alpha size in the material.

SwRI anticipates limited issues adding this capability into DARWIN, though it would require significant effort to design, implement, verify, integrate, and document the new approach. New DARWIN capabilities would build on earlier capabilities to assess lives and risk for cracks under cyclic FCG and TDCG mechanisms. Recent improvements to the DARWIN infrastructure support new analysis objectives and facilitate assessment modes that could not be supported prior to this reorganization. SwRI recognizes several challenges in obtaining the data needed to support the proposed assessment capability. These concerns are noted in the roadmap, along with an overview of the anticipated modifications to DARWIN needed to support these calculations.

1 Introduction

1.1 Cold dwell fatigue

Cold dwell fatigue (CDF) is a time-dependent process in near-alpha titanium alloys at temperatures below 300°C that involves metal degradation in the presence of creep to produce cracking on low-energy fracture (e.g., cleavage) facets in preferentially oriented, hard-alpha grains. It is a rarely occurring condition that can cause significant reductions in fatigue life of fielded aircraft engine rotors and fan blades. While experience has shown that it can potentially result in catastrophic rotor failure, well-established methods have not been developed to incorporate this failure mode into assessments of component life and fracture risk management.

Treating the CDF mechanism has become more urgent due to the recent incident during Air France flight AF066 on September 30, 2017 (Bureau d'enquêtes et d'analyses pour la sécurité de l'aviation civile, 2020). During this flight from Paris to Los Angeles, CDF in Ti-6Al-4V contributed to an engine failure that forced an emergency landing in Greenland. Metallographic examination of the recovered fan indicated that a crack originated 1.4 mm below the surface due to low-cycle fatigue processes and grew over 1,652 cycles (with one cycle taken as one striation) to final fracture. Since the AF066 incident, CDF in Ti-6Al-4V contributed to at least two failures in fan blades (UA1175 on February 13, 2018 and AF703 on March 10, 2019).

The AF066 crack started in a large microtextured region (MTR) that promoted material degradation processes. MTRs are colonies of similarly oriented grains of the hexagonal close-packed alpha-phase of Ti-6Al-4V. Among several contributing factors, there is the (common) assumption that the CDF mechanism was not present in titanium alloys with a residual body-centered cubic beta-phase, e.g., Ti-6Al-4V. However, the AF066 incident and other recent investigations reveal that the MTRs inTi-6Al-4V can promote CDF, and large titanium forgings of Ti-6Al-4V increase the risk of the large MTRs. Consequently, some recent engines have been manufactured using Ti-6Al-4V without CDF considerations that, had they been present, may have led to design or usage modifications. Non-destructive methods to detect MTRs are unavailable, and certification bodies have not provided instructions on treating CDF mechanisms in critical engine parts.

CDF activates in MTRs aligned with the primary stress direction, usually the hoop direction in rotor applications. MTRs support a complicated slip transfer process between strong and weak slip systems that ultimately underlie the CDF process. Lavogiez et al. (2020) characterize the deformation mechanisms of CDF in Ti-6Al-4V under fatigue and dwell loadings. This study found that load hold duration activated basal and prismatic slip in some α-grains, and these slip systems redistributed stresses from the soft grains (with basal and prismatic slip) to hard grains (with pyramidal slip and twinning). This load shedding process reduces the number of cycles to crack nucleation and increases crack growth rates under dwell conditions.

The impact of CDF on component lives can be assessed using either a fatigue approach that focuses on microstructural heterogeneities or a crack growth approach that assumes an initial anomaly. Fatigue approaches have shed light on the CDF process (Lavogiez, Hemery, & Villechaise, 2020; Zhang, Cuddihy, & Dunne, 2015; Zheng, Stapleton, Fox, & Dunne, 2018; Xu, et al., 2020; Liu & Dunne, 2021; Venkatesh, et al., 2020; Maloth, et al., 2020). However, fatigue approaches rely on microstructure characterization that may not be available in practice and that incur significant computational costs that limit their applicability. Crack growth approaches (Pilchak, 2014; Pilchak, Hutson, Porter, & Buchanan, 2016; Wang, Wang, Cui, & Tian, 2015). may provide a tractable approach to treat the CDF problem by treating CDF as a combination of small crack growth (SCG), fatigue crack growth (FCG), and time-dependent crack growth (TDCG) in MTRs. Specifically, the crack growth approach assumes that the CDF mechanism triggers a TDCG mechanism that is otherwise not present in these alloys. TDCG accelerates crack growth rates in critical MTRs above the rates observed in non-critical MTRs under dwell loadings.

1.2 Southwest Research Institute® involvement

The Federal Aviation Administration (FAA) has been funding research in probabilistic rotor integrity by Southwest Research Institute (SwRI®) and a team of aircraft engine manufacturers for many years. One of the key outcomes of this work has been a probabilistic damage tolerance (PDT) computer code called DARWIN®(Design Assessment of Reliability With INspection). DARWIN integrates finite element (FE) models and stress analysis results, fracture mechanics models, material anomaly data, probability of anomaly detection, and uncertain inspection schedules with a user-friendly graphical user interface (GUI) to determine the probability-of-fracture of a rotor disk as a function of operating cycles with and without inspections. DARWIN is now used to characterize fracture risk for several rare but significant threats to rotor integrity, including threats from rare microstructural anomalies in titanium rotors.

DARWIN features capabilities to treat a significant array of threats to engine applications. Specifically, DARWIN already includes capabilities to treat SCG, FCG, and TDCG for cracks present anywhere in the rotor using approximate engineering solutions of the stress-intensity factor solution. This capability includes important considerations for data input (through a user-friendly GUI) and post-processing that enable analysts to view critical information needed to investigate the result. Investments in DARWIN capabilities since 1995 exceed $50 million and have led to the development of a tool used throughout the world to design and certify engine components.

The Air Force Research Lab (AFRL) tasked SwRI to investigate the feasibility of integrating a specialized crack growth approach into DARWIN to assess the impact of CDF on life and risk assessments. This effort involved investigating the model proposed by AFRL, practical considerations of its implementation, and discussions with third parties (i.e., Pratt & Whitney [P&W]) to provide industry perspectives. The effort was funded jointly by AFRL and the FAA. This report outlines this methodology and outlines improvements to DARWIN that are needed to support this effort. This report first outlines background information used in the CDF methodology, focusing on models for SCG, FCG, and TDCG supported by AFRL. The next section outlines the methodology by describing the final objective of these calculations, discussing deterministic assessments of life in critical MTRs, and then building on the previous section to consider probabilistic risk calculations. We then detail critical inputs needed to support these assessments and outline major modifications to DARWIN. This report closes with a brief list of challenges this effort has identified and a sample DARWIN input file for a prototype software concept.

It should be noted that this document represents a concept document for the CDF approach proposed by AFRL. This document is not a design document that includes the relevant specifications needed to implement, verify, and integrate new features into DARWIN. Instead, the current document outlines our understanding of the AFRL approach following several months of conversations between SwRI, AFRL, and P&W (who now employs Adam Pilchak, the original architect of this CDF framework). This document is the first step towards integrating a CDF capability into DARWIN, and future work (including modifications to the concept) would be based on this document or a revision thereof. We anticipate that this document will be reviewed by AFRL, the FAA, and other industry partners, and we look forward to future discussions.

2 Background

2.1 Crack growth components

This work relies on the model proposed by Pilchak and co-workers (Pilchak, 2014; Pilchak, Hutson, Porter, & Buchanan, 2016) that treats CDF as a crack growth issue amenable to damage tolerance (DT) approaches. DT almost always treats anomalies as cracks present in the material from the initial flight. This conservative approach ignores the long lives associated with crack formation. It captures the rare event where the following conditions all occur:

- the inspection process misses a critical anomaly;
- the anomaly is located in an MTR that is properly aligned to support CDF mechanisms;
- the MTR is large enough to drive significant crack growth under the imposed loading;
- and the imposed loading triggers a stress higher than the threshold stress for CDF.

It is these rare events that drive fatigue processes in the scenarios that limit lives. Since MTRs These rare events drive fatigue processes in the scenarios that limit lives. Since MTRs cannot currently be detected non-destructively, this conservative approach represents a reasonable engineering approach that trades conservatism for a tractable solution.

The AFRL approach considers three crack growth mechanisms: FCG, SCG, and TDCG. FCG mechanisms increase the crack size under cyclic loading conditions that are decoupled from the time-duration. FCG mechanisms are often focused on the long-crack regime that may have lower FCG rates than short cracks at equivalent driving force values. Consequently, an SCG mechanism must be introduced if small cracks represent critical anomalies. The small crack mechanism accelerates crack growth at small cracks that have been shown to have higher crack growth rates than larger cracks at equivalent loadings. Finally, the TDCG mechanism increases the crack size under constant loading conditions. In most metals, TDCG occurs at higher temperatures, promoting creep-like effects in the process zone ahead of the crack. However, in the case of certain titanium alloys, TDCG can occur in preferentially oriented microstructures at lower temperatures if stresses are sufficiently high. Therefore, CDF in titanium alloys occurs at a low temperature range.

AFRL selected well-established models with minimal inputs to support CDF assessments. Alternative models may be proposed as well, though these models will not be discussed in this work. Typically, the AFRL models feature variable inputs that will be discussed later in this report.

Let the crack size be denoted as a. AFRL adopts the Paris equation for FCG:

$$\frac{da}{dN} = C \times \Delta K^{n}. \qquad 1$$

Here, C and n are material constants determined by testing for a particular metallic alloy. These parameters have been shown to depend on temperature and are typically correlated. The C term in the AFRL model is taken as $C = 10^c$, with c being the actual material property entered into the DT assessment, though this represents a simple scaling of the term C that is normally used. The term ΔK reflects the cyclic variation of the stress-intensity factor, K, due to the loading spectrum. The value of K is usually evaluated at a tip-by-tip basis at specified locations around the crack front to determine the cyclic crack growth rate, da/dN, that indicates the amount of crack growth from a cycle of fatigue loading.

Another key FCG parameter is the threshold toughness (ΔK_{th}) that must be overcome for any FCG to occur during a cycle:

$$\frac{da}{dN} = 0 \text{ if } \Delta K \leq \Delta K_{th}. \quad 2$$

The value of ΔK_{th} is usually determined through test by extrapolating the measured FCG rate down to some appropriately low da/dN value as is done in certain ASTM standards (ASTM International, 2016).

The material constants C and n are typically determined for long cracks. A SCG correction can be implemented using the El Haddad parameter to increase the driving force for FCG, ΔK:

$$\Delta K = F \times \Delta\sigma \times \sqrt{\pi(a + a_0)}. \quad 3$$

Here, F is the geometry correction factor, $\Delta\sigma$ is the stress range, and a is the measured crack length. The parameter a_0 is known as the El Haddad parameter and reflects a length scale around which SCG behavior is distinctive. The El Haddad parameter increases the driving force for FCG for small cracks ($a \leq a_0$), and this effect decreases as $a \gg a_0$. SCG may be suppressed by setting the value of $a_0 = 0$.

The values of C, n, and a_0 for cyclic crack growth are taken to be identical inside and outside of critical MTRs. Consequently, the current approach accelerates crack growth inside of critical MTRs only by supporting the TDCG mechanism. Here, the crack growth rate per unit time is set as:

$$\frac{da}{dt} = C_d \times K_{max}^{n_d}. \quad 4$$

$$K_{max} = F \times \sigma_{max} \times \sqrt{\pi(a + a_{0d})} \quad 5$$

These equations represent a simple, Paris-like equation for the CDF process driven by TDCG properties and was proposed by Pilchak and co-workers (Pilchak, 2014; Jha, Golden, Larsen, & John, 2023). A similar approach taken by Wang et al. (2015) involves many more material parameters but is otherwise equivalent.

The terms C_d, n_d, and a_{0d} reflect material properties for the CDF mechanism. These terms need to be determined within a critical MTR under dwell loading conditions. These terms are also expected to be dependent on the temperature. The value of σ_{max} (which maps onto K_{max}) reflects the maximum stress during dwell. Similar to FCG, the coefficient C_d for TDCG may be expressed as $C_d = 10^{c_d}$.

TDCG may feature a stress threshold, σ_{th}, below which there is no TDCG:

$$\frac{da}{dt} = 0 \text{ if } \sigma \leq \sigma_{th}. \tag{6}$$

Here, the stress is taken at the center of the crack. If the stress at the crack center does not equal or exceed the stress threshold value, then there will be no contribution to crack growth from dwell. The dwell stress threshold will be temperature dependent. To avoid double counting, the dwell stress threshold approach prohibits a threshold value based on the stress-intensity factor for TDCG. (FCG may still employ a threshold stress-intensity factor.)

The total crack growth increment (da) from a dwell cycle is determined by adding the contribution from FCG and TDCG over the cycle duration (Δt):

$$da = \frac{da}{dN} + \frac{da}{dt} \times \Delta t. \tag{7}$$

The DT assessment updates the crack size and shape based on the crack growth increment predicted by this expression. There is a saturation time limit, Δt_s, and the maximum value of Δt will be set to Δt_s. Consequently, there can be no dwell contributions to crack growth beyond this time limit. The dwell saturation time limit will be taken to be temperature independent. The potential variability of these terms will be discussed in Section 4.3 of the report.

2.2 Approach to microtextured regions

Microtextured regions (MTRs) reflect grains or grain groups in the microstructure that could have an orientation favorable to CDF. We will not focus on the technical aspects of MTRs here. Instead, we will focus on the information suggested by AFRL to define critical MTRs, i.e., MTRs that promote CDF:

- MTR size, provided as equivalent diameter;
- Grouping density, provided as a fraction between 0 and 1;
- C-axis inclination, provided as an angle between 0° and 90°.

Note that the MTR size has already been determined in the above information. The MTRs must be classified as critical or non-critical. AFRL recommends defining a critical MTR as a region with a grouping density below some threshold or a c-axis inclination above some critical angle. Here, the critical angle is assumed to be aligned with some datum informed by the loading state, perhaps defined by the maximum principal stress direction. Consequently, if the loading state changes, then the c-axis inclination would change, in turn changing which MTRs are defined as critical or non-critical.

If there is a critical MTR, two potential methods exist to define the critical MTR used during DT assessments.

- In the distributed critical MTR concept, critical MTRs are distributed along the crack path based on some reconstruction of the microstructure, with reconstructions ranging from very crude to very elaborate. The distributed critical MTR concept requires more information to define the MTRs and significant computational effort to reconstruct microstructures. Depending on the quality of the reconstruction, the distributed critical MTR concept may provide a more realistic description of CDF mechanisms on crack growth rates.
- In the equivalent critical (EC)-MTR concept, the critical MTR size is set based on a circle placed at the center of the crack, with the circle diameter provided by the critical MTR size. The EC-MTR concept requires upfront work to agglomerate the area from separate MTR regions into a single area. It is relatively straight forward to implement during DT assessments and utilizes simple data structures. The EC-MTR concept should provide conservative (if not overly conservative) predictions since it accelerates small cracks (within the lowest growth rates) as opposed to large cracks.

We adopt the EC-MTR approach for DT assessments here due to its simplicity, straightforwardness, and conservatism.

Figure 1 illustrates the EC-MTR concept. Here, a crack is placed into critical MTR in the actual microstructure shown on the left. If the crack were to grow through this critical MTR region, its rate would slow down once crack tips were outside of the critical MTR boundary and would not speed up again until the tips were inside of another critical MTR. Since critical MTRs are spread throughout the material, the crack tips speed up and slow down regularly. This process implies that the crack tips are checked continuously to ensure they are within the critical MTR. On the right side of Figure 1, the critical MTR is converted into an EC-MTR, with the areas from the left merged into a single critical MTR on the right. The EC-MTR has the same area as the sum of the critical MTRs that could realistically be encountered by a crack during crack growth. Consequently, not all critical MTRs in a plane are agglomerated into an EC-MTR. The crack is located within the EC-MTR from the start of the analysis, and dwell effects do not stop and restart during the assessment. Dwell effects are active, terminate, and never restart in the EC-MTR concept.

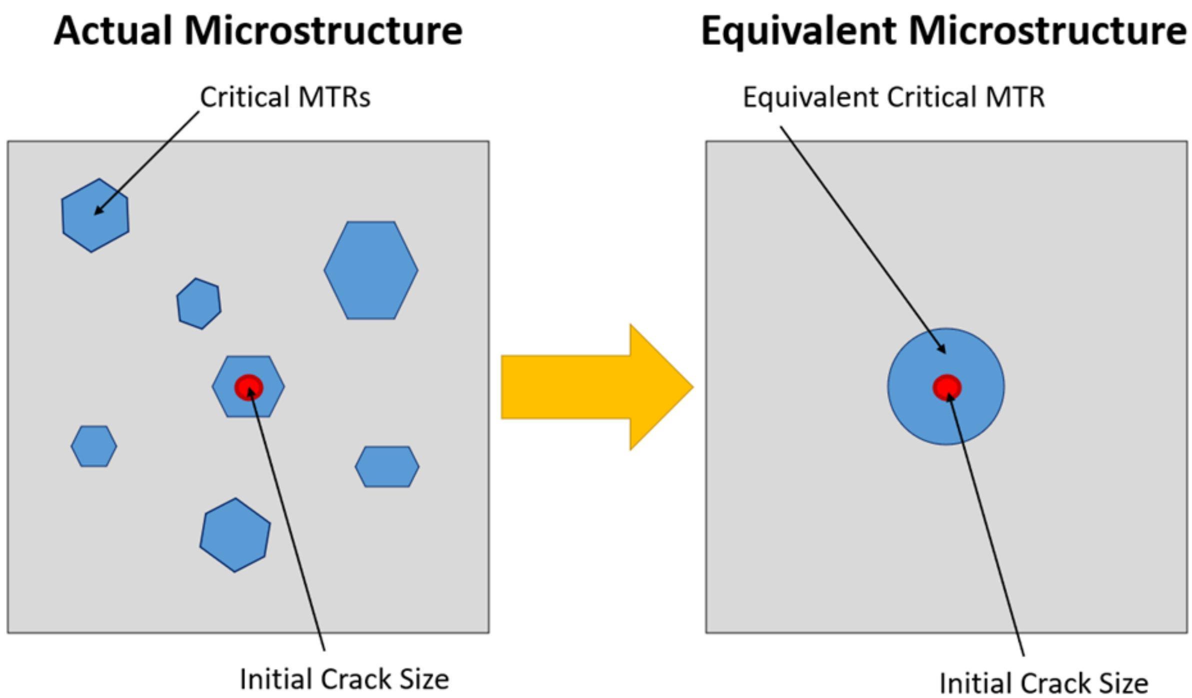

Figure 1. Equivalent critical MTR concept

It is assumed that the distribution of EC-MTRs will be characterized into an exceedance curve of EC-MTRs, i.e., the equivalent critical-exceedance curve (ECEC)-MTRs. Exceedance curves provide the likelihood of an EC-MTR being present and the distribution of EC-MTR sizes. DARWIN now employs the same approach to characterize anomalies during risk calculations. The ECEC-MTRs provide the information needed during sampling risk calculations. We assume that information might vary across the part, e.g., different curves at the rim *vs.* the bore.

Dwell terms are only active if a tip is within an EC-MTR. Once a crack tip is outside of the EC-MTR, dwell is suppressed and $da/dt = 0$. The DT assessment continues for a crack tip outside of the EC-MTR until a failure state is reached, e.g., fracture. Crack tips are independent, and if one crack tip grows outside of the EC-MTR, the remaining crack tips still may grow by TDCG mechanisms. Note that this is a hard boundary. The crack tip immediately transitions from growing in an EC-MTR (with dwell) to growing outside of an EC-MTR (without dwell).

3 Methodology

We anticipate that AFRL will require a deterministic DT (DDT) framework and a PDT framework. The DDT framework would be useful for calibration studies and field issues, while the PDT framework might be of interest for design, certification, and fleet usage studies. Here, PDT includes the min-Life approach implemented in DARWIN under AFRL funding. This section only highlights changes to DDT and PDT relative to the baseline (non-CDF) case.

3.1 Deterministic

A DDT analysis will need to be modified to accept the updated material model that includes FCG, SCG, and TDCG mechanisms. An earlier section describes these material properties and the underlying models for these mechanisms. To invoke time-dependent effects, users will need to enter a duration time for each loadcase in the mission history. DARWIN already enables users to enter this information for an analysis, which will be required for CDF. The duration time could and should be in the finite element file.

A DDT analysis will also need to be modified to include EC-MTR definition data. Here, the user would set the EC-MTR size for the crack under consideration. The EC-MTR size would likely be set when a crack is defined in DARWIN. It could be region specific for something like crack growth contours or min-Life calculations. Several EC-MTR sizes could be defined and analyzed to investigate the sensitivity of the analysis to these results. The user would provide the initial crack size based on the critical primary alpha grain size distribution in the material. The initial crack size refers to the starting crack size for fatigue crack growth assessment of a life assessment. Again, the initial crack size might be varied to determine the sensitivity of predicted lives to this input variable.

If a crack tip is not in an EC-MTR, then normal FCG calculations would be performed. This scenario could arise if the EC-MTR is small relative to the initial crack size or the crack shape is elongated, causing some tips to be outside of the EC-MTR. Alternatively, if the crack tip is in an EC-MTR, then the DDT would perform the assessment using the properties for FCG, SCG, and

TDCG outlined here to determine the dwell contribution. For some cracks, the applied stress may not exceed the threshold stress, and the DDT assessment would proceed without the dwell contribution.

Figure 2 shows a conceptual framework for a DDT iteration. Here, it is assumed that the crack starts within some EC-MTR and may grow outside of it. Consequently, each crack tip must be checked to determine if the tip remains within the EC-MTR. If not, the crack growth algorithm (e.g., Flight Life) would only compute the cyclic FCG rate. Next, the loading history needs to be checked to ensure that there is some dwell associated with at least one loading cycle. If all loading cycles are instantaneous, then the CDF mechanism cannot activate, and only FCG rates are computed. Finally, the stress acting on the crack must exceed the threshold stress; otherwise, only cyclic FCG is computed. We currently assume that the applied stress used for this comparison with σ_{th} is the nominal stress at the crack location in the direction perpendicular to the crack plane but in the corresponding uncracked body. For simplicity, the threshold stress could be checked against the maximum stress in the mission history. If the tip has passed the first three checks, then the crack tip has TDCG that needs to be computed, though the duration attached to TDCG should be no higher than Δt_s as shown in the figure. This process would be repeated for every tip and for every loading cycle until the crack reached some limit state.

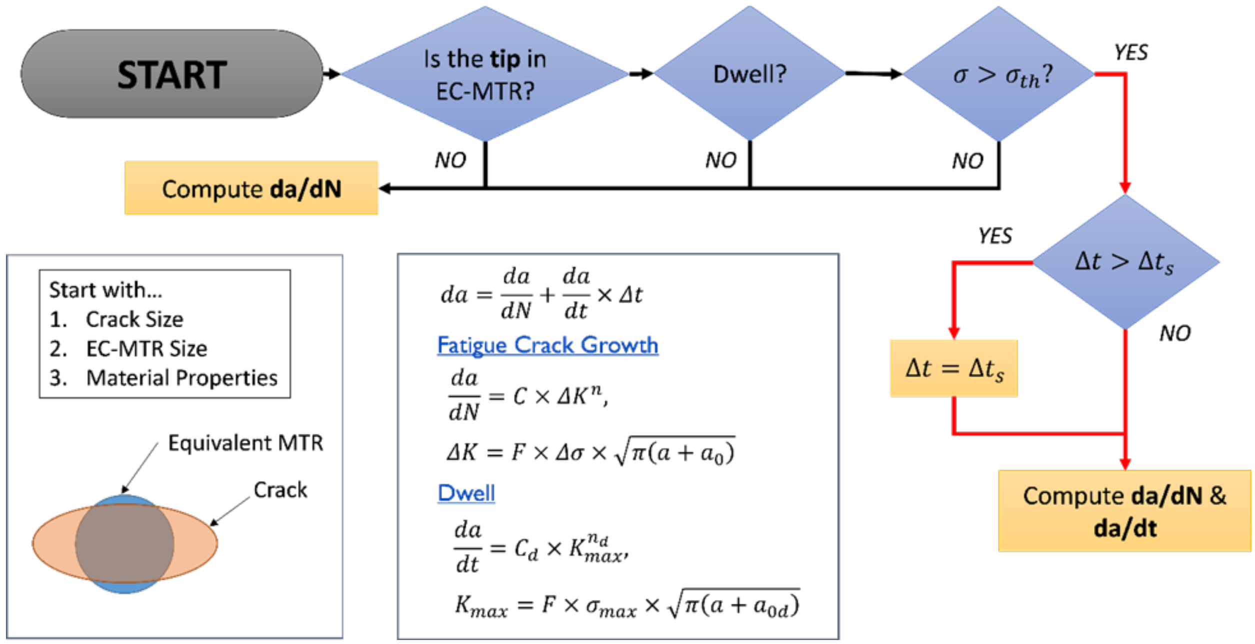

Figure 2. Conceptual framework of a DDT iteration to compute crack growth increment

The result of the DT assessment would be the life of a crack in a component in an EC-MTR. This life should be shorter than the life of a crack outside of an EC-MTR. While AFRL has not requested any new post-processing assessments, some modifications that could be useful:

- Indication of the MTR size during graphs of quantities of interest against life;
- Indication of the MTR size during animations.

3.2 Probabilistic

For probabilistic assessments, the goal is to compute the risk of fracture from CDF mechanisms. Practically, this will be accomplished by computing the risk for an anomaly of fixed initial size. The variability in lives will be driven by the ECEC-MTRs and other variability in material properties, loading, etc. The risk value produced by this methodology does not provide the overall component risk, i.e., the risk that would be provided by considering all potential modes of failure. The current approach of isolating CDF mechanisms (and the resulting risk number) follows similar approaches to other threats to structural integrity, i.e., treating hard-alpha anomalies (FAA AC 33.14-1) differently from surface damage (FAA AC 33.70-2).

A PDT analysis will need to be modified to define scatter in the material properties if it is present. Here, users would be responsible for defining the scatter in the coefficients as appropriate. A PDT analysis will also require an initial crack size for the calculation. As a first implementation, we suggest that the initial crack sizes be based on the primary alpha grain size distribution and independent of the MTR information. That is, the MTRs will not contribute in any way to the definition of the initial crack sizes. Furthermore, we will assume that all cracks will be present in the analysis from the first cycle. They are initial cracks, not formation cracks. This approach is consistent with PDT in DARWIN for hard-alpha particles and surface damage. In the future, it may need to be reconsidered for CDF. The initial crack size may need to vary from region to region to capture different processing zones.

A PDT analysis will need to accept the ECEC-MTRs. We recommend any cumulative distribution functions (CDFs) be defined using parametric distributions (e.g., normal, lognormal, Weibull) rather than using full CDFs defined by a piecewise linear curve. We recommend modeling the EC-MTR likelihood as a deterministic variable (i.e., number of MTRs per unit volume). The MTRs are not well-defined, and the tails may not be well-characterized (or understood). As a result, the critical information in the distribution will occur near mean values rather than at the tails. This information would need to be entered in addition to the anomaly distribution and the material model variability.

During a Monte Carlo (MC) iteration, the different distributions would be sampled: ECEC-MTRs, material properties, and other variable parameters. The sampled values would set the conditions for a DDT analysis. The final crack state would be stored and built into the resulting risk value at that location. This information would set the conditional risk at that point.

The unconditional risk would be defined by combining the conditional risk with the area surrounding the local risk limiting location and the occurrence rate in the ECEC-MTRs. An extremely conservative approximation would be to agglomerate the entire volume of the part at the risk limiting location of the component. Alternatively, zoning approaches could be used to split up the analysis, reduce risk, and maintain a conservative risk value. Zoning approaches are currently used in DARWIN for a variety of scenarios.

The result of the PDT assessment is a risk as a function of the mission history. Risk increases as the part is cycled through more missions. Risk may stop increasing if crack growth from early missions most contribute to fracture and there is little subsequent crack growth, e.g., due to threshold effects. Consequently, certification authorities may require an alternative measure of risk that provides the risk per flight to avoid too much risk on any one flight. Certification authorities may use either number or both numbers when setting policy.

Figure 3 shows the conceptual PDT framework for a single crack to compute the conditional risk value. Here, the PDT framework relies on MC sampling with the number of samples determined by the analyst prior to beginning the analysis. The number of samples will depend on the target risk and the confidence that the analyst requires for the result. Lower risk values at higher confidence levels will require more MC samples. In this figure, there are some pre-defined random variables: the ECEC-MTR, material property distributions, and other random variables. After a new MC sample starts, these distributions are sampled and drive the associated DDT run. In the DDT run, the initial crack size is set at some constant value and is immediately checked to see if it violates a limit state (i.e., fracture). If the crack does not violate a limit state, a crack growth increment is computed using the procedure outlined in Figure 2.

Crack growth continues until a limit state is violated, at which point the PDT assessment stores the life and inquires if another MC sample should be taken. The loop continues until all MC samples are taken, and then the risk (and other associated quantities) can be computed.

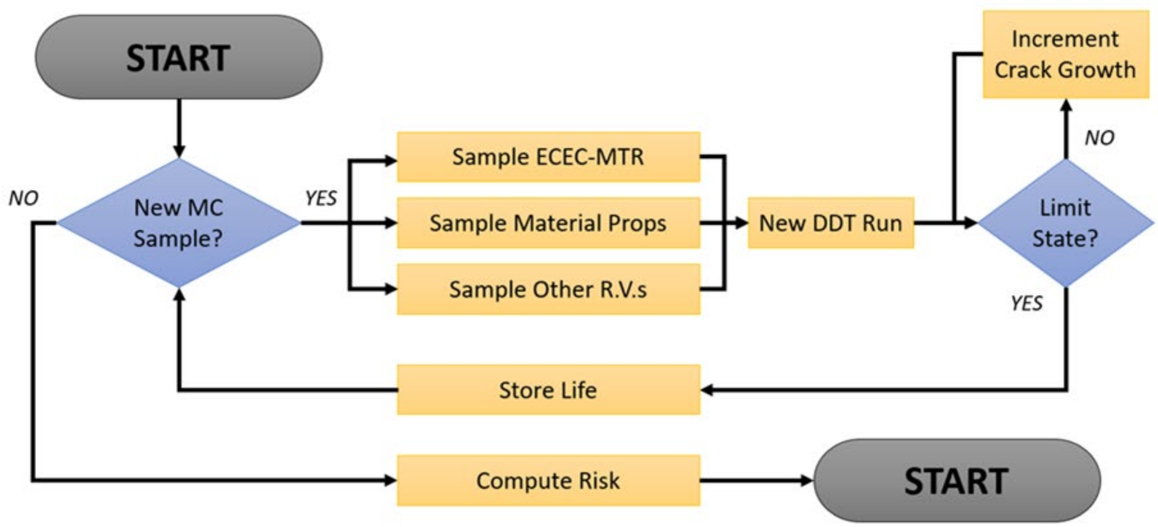

Figure 3. Conceptual framework of the PDT framework

4 Critical inputs

4.1 Equivalent critical-exceedance curve microtextured regions

The equivalent critical-exceedance curve microtextured regions (ECEC-MTRs) represent the main driver of variability in the anticipated PDT assessment. This information is somewhat analogous to the anomaly distributions that drive hard-alpha calculations in DARWIN today. The key difference is that the hard-alpha particles act as crack initiation sites. EC-MTRs increase crack growth rates in contrast. Unlike the hard-alpha calculations, the ECEC-MTR may have a higher occurrence rate since >10% of the entire component may be MTRs (Jha, Golden, Larsen, & John, 2023). This information must be provided for a PDT assessment in an acceptable format. Figure 4 provides a draft format that could be acceptable to DARWIN. Its format is based on the format for hard-alpha anomalies currently in DARWIN.

```
TITLE
Sample MTR Input File for Discussion with AFRL.

DESCRIPTION
This is a mock-up of the MTR input file. This file would be set by the
user and imported into DARWIN to establish a non-deterministic MTR. Bolded
keywords could have multiple inputs.

MODEL MTR
UNITS US
DOF AREA
DIST_TYPE NORMAL
REFERENCE VOLUME
LIKELIHOOD 0.01
MEAN 0.020
COV 0.005
```

Figure 4. Sample input file for ECEC-MTRs

The ECEC-MTR will be derived from information extracted by microstructural characterization techniques. There is currently no readily accessible methodology to extract information on the MTR size, c-axis inclination, and grouping density. However, there may be a pipeline to obtain this information soon using DREAM3D®. Assuming this information is available, it must be processed to obtain first critical MTR size and then the EC-MTR sizes that would inform the ECEC-MTR. These processing steps involve several stages:

1. Identify the **critical** MTRs. This stage converts the raw information from the electron backscatter diffraction (EBSD) scan and identifies MTRs that trigger TDCG. The result from this step is a list of all critical MTRs in the region. For simplicity, texture within some region is assumed to be uniformly distributed such that the following statement *could be* taken as correct: “This region (perhaps the bore) of material has some percentage of the MTRs that are critical MTRs, and this other region (perhaps the rim) has a different percentage of the MTRs that are critical MTRs.” Uniform does not mean homogeneous. Orientation is not allowed to vary significantly from point to point (except across region boundaries).

2. Merge critical MTRs into **equivalent** critical MTRs (i.e., EC-MTRs). This step lumps MTRs that are "close" to each other into a single equivalent MTR and adds the areas of individual MTRs into a single area that reflects the entire region. Here, close means close enough to impact crack growth rates. Consequently, there is likely some length scale to be determined that indicates if MTRs can influence crack growth from a crack in a different MTR. This length scale avoids the non-sensical proposition that the crack growth rate at one critical MTR can be impacted by a different critical MTR that is many times the crack size at fracture away.
3. Build a **distribution** of EC-MTRs. Here, the sizes of EC-MTRs would be ordered and described by some distribution to be determined. This distribution may fit easily into classical distributions (e.g., the Weibull distribution) or be described using some other relationship.
4. Build an **exceedance curve** of EC-MTRs (i.e., the ECEC-MTRs). Again, the exceedance curve represents the sizes of EC-MTRs and their occurrence rate. Both pieces of information are needed to determine unconditional risk of fracture from CDF mechanisms.

4.2 Fatigue crack growth properties

Fatigue crack growth (FCG) properties can be determined using standard ASTM E647 (ASTM International, 2016) tests of the titanium alloy. The test should focus on the material properties supported by the Paris model, specifically:

- $c = \log_{10}(C)$, with C representing the y-axis offset of the da/dN vs. ΔK curve in log-log space.
- n, that represents the slope of the da/dN vs. ΔK curve in log-log space.
- a_0, the El Haddad parameter.
- ΔK_{th}, the threshold toughness value.

AFRL suggests that the FCG model incorporates variability into its computations. Specifically, the PDT assessment should enable the Paris model to shift up and down based on the sampling. Previous efforts that consider FCG rate variability demonstrate that the variables c and n are highly correlated. It may be useful to consider the variability of just one parameter and to use a correlation coefficient to determine the appropriate scaling of the other parameter.

Several of these parameters (c, n, and ΔK_{th}) vary with the temperature. The material properties should be provided over a range of temperatures that cover the component. Furthermore, material properties will need to be interpolated over the range of temperatures in the component, and several options are available to perform this operation. Finally, the FCG computations require a thermal-mechanical fatigue (TMF) algorithm to determine the appropriate temperature. These considerations will, in general, be determined by the organization tasked with assessing the component.

The stress ratio (R) of any stress cycle alters the fatigue crack growth rate (i.e., increasing or decreasing the value at a constant value of ΔK_{th}), that in turn impacts the values of these parameters as well (c, n, and ΔK_{th}). If R is a single value, then no additional properties or models are needed. However, most components will have sufficient variability in their loading histories that additional data and/or models are needed to support R effects. Again, these decisions will be determined by the organization responsible for the analysis.

While not mentioned so far, the existence of FCG properties presumes toughness properties. Toughness properties often vary with temperature. Lower bound toughness values can be obtained via standard testing methods (ASTM International, 2022; ASTM International, 2019). The lower-bound toughness value may be too conservative for thinner structures, and corrections may be applied to achieve physically realistic toughness values in thinner structures with less constraint.

4.3 Time-dependent crack growth properties

Researchers must use specialized methods to achieve time-dependent crack growth (TDCG) properties for CDF. ASTM E2760 (ASTM International, 2020) outlines a testing procedure to measure creep-fatigue crack growth in metals using conventional large specimens, which may not be practical for MTRs. Instead, specimens will likely be sub-sized and use small surface cracks with focused ion beam (FIB) notches as crack starters. There may be multiple cracks in the same specimen if crack growth rates can be measured independently for each crack and crack fields do not interact. Cracks must be placed in a critical MTR to measure CDF TDCG properties. Cracks not located in critical MTRs will not activate the CDF mechanism. These considerations may lead to the development of new, specialized standardized tests.

Properties measured from these tests include:

- $c_d = \log_{10}(C_d)$, with C_d being the y-axis offset of the da/dt vs. K_{max} curve in log-log space.

- n_d, that represents the slope of the da/dt vs. K_{max} curve in log-log space.
- a_{0d}, the El Haddad-like parameter for TDCG.
- σ_{th}, the threshold stress value.

AFRL suggests that the TDCG model incorporates variability into its computations. Specifically, the PDT assessment should enable the TDCG rate and intercept to change. It may be useful to consider the variability of just one parameter and to use a correlation coefficient to determine the appropriate scaling of the other parameter.

These parameters vary with temperature. It is well-known that CDF only activates in a narrow range of temperatures, and it is expected that the parameters in the CDF TDCG model will as a result vary non-monotonically with temperature. Non-monotonic variation of TDCG rates with respect to temperature is different from the normal response of TDCG and may pose special challenges with respect to testing. Specifically, many tests may need to be performed to determine the maximum TDCG rate.

The saturation time (Δt_s) seems somewhat straightforward to determine based on testing: measure TDCG rates at various dwell times and determine the dwell time at which TDCG ceases. Unfortunately, this approach will require several tests at progressively longer dwell times to determine Δt_s. It may be necessary to determine Δt_s at various temperatures as well.

It is unclear how to measure the threshold stress value. The presence of a crack and its associated crack-tip fields substantially alter stresses near the crack. Predicting or measuring stresses near an actual crack is particularly difficult and probably not practical. The straightforward method to apply a threshold stress criterion, as mentioned earlier, is to compare the stress at the crack location in the corresponding uncracked body against the threshold stress. By implication, the threshold stress would need to be measured in an uncracked body, and the value of σ_{th} would be measured by detecting the stress at which dwell cracks first form and begin to grow by CDF mechanisms. This approach further implies that TDCG would not suddenly begin after FCG mechanisms had advanced a fatigue crack. It is also possible that the stress in the uncracked body varies on a highly localized basis due to the microstructure, but this would be difficult to characterize and incorporate with the bulk stresses provided by continuum finite element analyses. Clearly, there are several unresolved questions here about the meaning, measurement, and application of the threshold stress.

4.3.1 Sample material input file

This section provides a sample material input file, Figure 5, Figure 6, and Figure 7, to demonstrate the information that would be needed to support the CDF model detailed in this report. This same file follows standard DARWIN conventions, and while it only provides a preliminary example, it is unlikely that the fundamental structure of the material file presented here would be altered significantly. Numbers present in this file are arbitrary and do not necessarily reflect a known material system.

```
TITLE
Ti64 Mock-up

DESCRIPTION
Ti64
Paris FCG eqn. with scatter
Walker Interpolation stress ratio eqn.
Dwell inside of the MTR

UNITS                  US

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~!
DADN DATA
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~!
!~~~~~~~~~~~~~~~
! dadN for air
!~~~~~~~~~~~~~~~
AIR

FCG_FORMAT                       PARIS_RANDOM
C_FORMAT                         EXPONENT
XC_MEAN                          1.1
XC_STDEV                         0.1
RHO                              -0.1
STRESS_RATIO_FORMAT              WALKER_INTERPOLATE
TEMPERATURE_INTERPOLATION_FORMAT CLOSEST

TEMPERATURE 75.0
TOUGHNESS   59.2
!C    n   delta_Kth R_Ratio a0
-10.6 4.5 12.6      0.03    0.0015
-10.5 4.6 12.5      0.75    0.0015

TEMPERATURE 400.0
TOUGHNESS   55.1
!C    n   delta_Kth R_Ratio a0
-10.4 4.7 12.4      0.03    0.0016
-10.3 4.8 12.3      0.75    0.0016

!~~~~~~~~~~~~~~~~~~
! dadN for vaccum
!~~~~~~~~~~~~~~~~~~
VACUUM

FCG_FORMAT                       PARIS_RANDOM
C_FORMAT                         EXPONENT
XC_MEAN                          1.1
XC_STDEV                         0.1
RHO                              -0.1
```

Figure 5. Sample CDF model material input file (part 1)

```
STRESS_RATIO_FORMAT               WALKER_INTERPOLATE

TEMPERATURE_INTERPOLATION_FORMAT CLOSEST

TEMPERATURE 75.0
TOUGHNESS   59.2
!C    n   delta_Kth R_Ratio a0
-10.6 4.5 12.6      0.03    0.0015
-10.5 4.6 12.5      0.75    0.0015

TEMPERATURE 400.0
TOUGHNESS   55.1
!C    n   delta_Kth R_Ratio a0
-10.4 4.7 12.4      0.03    0.0015
-10.3 4.8 12.3      0.75    0.0015

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~!
MTR DADT DATA
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~!

MODEL       PILCHAK_RANDOM
C_FORMAT                        EXPONENT
XC_MEAN                         1.2
XC_STDEV                        0.1
RHO                             -0.2

STRESS_THRESHOLD             10.0
DWELL_SATURATION_TIME        300.0
TEMPERATURE_INTERPOLATION_FORMAT CLOSEST

!Cd nd a0d Temp
-10.9 3.7 0.0015 75.0
-10.8 3.8 0.0016 400.0

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~!
! Monotonic stress strain.                                                    !
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~!
STRESS_STRAIN_MONOTONIC
INPUT_FORMAT           RAMBERG-OSGOOD
TEMPERATURE_INTERPOLATION_FORMAT CLOSEST
!epsilon0 sigma0 alpha n yield Temp
 0.008647 147.0019 1.0 30.0 140.0 70.0
 0.008009 136.1534 0.99 30.0 130.0 200.0
 0.009013 126.1755 0.99 30.0 120.0 600.0
 0.008754 105.0442 0.99 30.0 100.0 1200.0

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~!
! Cyclic stress strain.                                                       !
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~!
```

Figure 6. Sample CDF model material input file (part 2)

```
STRESS_STRAIN_CYCLIC
INPUT_FORMAT           RAMBERG-OSGOOD
TEMPERATURE_INTERPOLATION_FORMAT CLOSEST
!epsilon0 sigma0 alpha n yield Temp
 0.008647 147.0019 1.0 30.0 140.0 70.0
 0.008009 136.1534 0.99 30.0 130.0 200.0
 0.009013 126.1755 0.99 30.0 120.0 600.0
0.008754 105.0442 0.99 30.0 100.0 1200.0
```

Figure 7. Sample CDF model material input file (part 3)

4.3.2 Initial crack size

The initial crack size reflects the microstructural features of the alloy that act as cracks from cycle zero. Specifically, the initial crack size may be related to the size of primary alpha grains in the material. The average size of primary alpha grains is on the order of 25 microns, though larger sizes are possible, and AFRL suggests a value of 40 microns.

5 Needed DARWIN modifications

Based on the approach outlined above, we anticipate the following changes to DARWIN would be needed:

1. Capability to activate the CDF enhancements.
2. New capabilities to input a deterministic EC-MTR size.
3. New capabilities to input an ECEC-MTRs for a risk assessment. A draft of the input file is provided in.
4. New capability to define an EC-MTR for DT assessments, with the EC-MTR placed at the center of the crack and modeled as a circle.
5. New capabilities to determine if a crack tip is inside of an EC-MTR during crack growth assessments.
6. New material model flag in the material properties file that indicates if the material properties contain information for the CDF model.

7. New time-dependent capability using the TDCG model outlined above that includes a SCG parameter for TDCG.
8. New dwell saturation time limit, Δt_s.
9. New dwell stress threshold, σ_{th}.
10. Capabilities to support material variability as follows:
11. Variable C (with correlation to n)
12. Variable C_d (with correlation to n_d)
13. Temperature dependence and R-ratio dependence of several material parameters for FCG and TDCG, i.e., C, n, C_d, n_d, ΔK_{th}.
14. Temperature interpolation using existing capabilities in DARWIN (e.g., *NEAREST*).
15. The new modeling capabilities using the existing TMF algorithms in DARWIN, e.g., *TEMPERATURE AT MAXIMUM STRESS* in DARWIN.
16. Several material properties are not anticipated to require temperature dependence and R-ratio dependence: i.e., a_0, a_{0d}, Δt_s, and σ_{th}.
17. Enhanced DDT assessment as described above.
18. Enhanced PDT assessment as described above.
19. Full documentation to support this approach.

We do not anticipate any additional output from a DDT analysis or from a PDT analysis in DARWIN. Draft input files for the material properties are provided in Figure 5, Figure 6, and Figure 7. New information specific to the MTR is highlighted in Section 4.2 and 4.3.

6 Challenges

SwRI anticipates limited issues adding this capability into DARWIN, though it will require significant effort to design, implement, verify, integrate, and document the new approach. New DARWIN capabilities build on earlier capabilities to assess lives and risk for cracks under cyclic FCG and TDCG mechanisms. Recent improvements to the DARWIN infrastructure support new analysis objectives and facilitate assessment modes that could not be supported prior to this reorganization.

SwRI recognizes several challenges associated with obtaining the data needed to support the proposed assessment capability:

- Exceedance Curves for Equivalent Critical Micro-Textured Regions, i.e., the ECEC-MTRs. Currently, these curves are entirely hypothetical. While it is possible to determine portions of the raw input (MTR size, c-axis inclination, and grouping density) using boutique methods, there is apparently no current capability to characterize this information using a direct workflow. Furthermore, once this raw information is available, it still needs to be processed into the ECEC-MTRs format. The process to perform this transformation has not been outlined and will require agreement from industry and government before it is standardized. It is unclear if a master ECEC-MTRs curve can be produced to quantify Ti-6Al-4V or if this curve will need to be generated by each OEM.
- TDCG properties for CDF mechanisms. Pilchak measured TDCG at FIB notches placed into critical MTRs and cycled these specimens under a dwell-fatigue loading history. This test yielded da/dN curves that then needed to be processed to achieve the TDCG properties for c_d, n_d, and a_{0d}. This testing method will need to be standardized since the current ASTM testing standard for creep fatigue does not consider critical features of the CDF mechanism. The analysis approach to extract c_d, n_d, and a_{0d} from the raw data will need to be systematized as well. The resulting approaches will need to be cost effective if sufficient data needs to be generated to consider variability in the material response.
- As mentioned above, the determination of the σ_{th} and its interpretation is an open question. SwRI has approached it as a criterion for crack nucleation that permits ready measurement from simple experimental investigations. However, this interpretation may need to be reviewed to ensure that it is consistent with the remainder of the DT approach to CDF.

SwRI also has one concern regarding the definition of a critical MTR in relation to the loading. It has been stated that a critical MTR will have a c-axis orientation with respect to the plane of principal stress (often aligned with the hoop stress for axisymmetric discs) that promotes crack growth. We anticipate that this dependence on orientation could prove challenging to the development of a component-agnostic, but material specific ECEC-MTR (with material here meaning the same alloy created using the same processing route). Things become more difficult if the uniform distribution assumption is not correct. Current AFRL guidance is to assume a uniform distribution for demonstration of the proposed methodology. We anticipate the use of more complex approaches in the future for accurately predicting the data.

7 Summary

This report summarizes recent efforts by SwRI to review critically the AFRL approach that treats CDF as a DT problem. In this approach, cracks initiate in critical MTRs that promote TDCG processes that do not occur outside of the critical MTR. The TDCG process accelerates crack growth under dwell loadings. FCG, SCG, and TDCG models describe crack growth rates using standard equations that permit control over several key features of the process through the input material properties. In the AFRL approach, MTRs are modeled (for simplicity) as circular regions that are centered at the crack and that have an area equivalent to the area that would be encountered by a crack using a distributed MTR approach. The AFRL approach enables deterministic DT assessments of life or probabilistic DT assessments of risk.

This report identifies information needed to support the AFRL approach. This information differs depending on the objective, and we focused on probabilistic DT assessments that require the most information in general. Critical new information required to support the AFRL model includes:

- ECEC-MTR – These curves permit risk assessments to vary the initial size of the EC-MTR. Crack tips inside of the EC-MTR have TDCG mechanisms that activate during dwell fatigue cycles.
- FCG, SCG, and TDCG material properties – These properties set model coefficients and control crack growth rates. Specialized testing may be required to measure these coefficients.
- Initial crack size – The initial crack size may be set based on the primary alpha grain size.

This report raises some concerns regarding the data needed to support these assessments and how the data will be obtained from test programs. The raw data suggested by AFRL to support the CDF model is not commonly collected, and since it is not commonly collected, standard processing methods or storage formats are not readily available. We anticipate difficulties acquiring this information. We raise these concerns based on our experience supporting fatigue and fracture control programs in government and industry.

We have found that the AFRL approach is amendable to a DARWIN implementation, though not without some modifications detailed in this report. These modifications would enable DARWIN to support the AFRL modeling approach. These modifications reflect our current view of the scope of work. We anticipate additional challenges to arise during a future detailed design that might require additional modifications beyond the list presented here. Detailed design for DARWIN implementation is outside of the scope of work.

Throughout this project, we have sought to limit the complexity of this model without sacrificing major physical considerations. More complex models are more difficult to manage; are more challenging to fit within existing paradigms; are more likely to generate push-back from outside entities; and are less likely to be adopted by industry and government. In our view, the current approach represents a first pass to treat this problem. We expect changes to the AFRL approach as it reaches the wider community that is interested and experienced with the CDF problem.

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