History, Phenomenology, and Status of Research on the Cold Dwell Fatigue Failure in Titanium Alloys

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ABSTRACT

The good balance of strength, ductility, and fatigue performance makes titanium alloys a great choice for gas turbine engines' fan and compressor section. Indeed, they have found widespread success in these applications, but since the 1970's there have been sporadic issues due to a phenomenon known as "cold dwell fatigue" (CDF). Having resulted in a number of uncontained engine failures, this longstanding issue has generated considerable research interest in the aerospace materials supply chain. A clear picture of the failure mechanism has emerged through decades of sustained government, corporate, and academic research activities. The root cause is a complicated alignment of composition, microstructure (and specifically the aggregation of similarly oriented grains into so-called "microtextured regions" or MTRs), stress, temperature, and stressed volume of material. Such a configuration is statistically rare and hence, fortunately, CDF failures are also rare. Nevertheless, CDF is an important failure mechanism to consider for the design and lifing of fan and compressor disks. This paper summarizes the history, phenomenology, and current understanding of CDF and conclude with a discussion of design and sustainment considerations.

1.0 INTRODUCTION

Titanium (Ti) is used to manufacture critical rotating components in military and commercial gas turbine engines. Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo, in particular, are used for fan and compressors disks. In order to reduce weight and increase performance, these components may be manufactured as integrally bladed rotors (IBR's) in advanced engines. Because of the large size of these components and the high cost of titanium, it is desirable to minimize the amount of scrap material and hence the disk and blades are manufactured separately and then joined via linear friction welding. This manufacturing route is also preferred to individually control the microstructure of the disk and blades to optimize for low- and high-cycle fatigue performance, which are the life-limiting design considerations, respectively.

Despite having high strength, good fatigue and fracture performance, and exceptional corrosion resistance, Ti alloys have one major Achilles' heel in that they are susceptible to ambient temperature creep at stresses below the yield strength. This is because of the anisotropy in critical resolved shear stress (CRSS) among the various families of slip systems in the hexagonal close packed alpha phase. Specifically, the {10-10}<11-20> and (0001)<11-20> have relatively low CRSS while the first- and second-order pyramidal <c+a> slip systems, which are necessary to accommodate plastic deformation along the [0001] c-axis of the HCP crystal, have higher CRSS. Thus, depending on stress level, a varying fraction of grain orientations are susceptible to creep deformation. Rotating Ti alloy components also experience high, sustained stresses during take-off at a time when the engine is relatively cool compared to its near-steady-state operating temperature and hence there are micromechanical effects not considered by current design or sustainment practices that are contributing to damage accumulation.

The intent of the present paper is to bring awareness to the “cold dwell fatigue” (CDF) failure mechanism by providing a brief historical overview, discussing the micromechanisms crack nucleation and propagation, and finally offering a few considerations for aeroengine design and sustainment to reduce susceptibility to CDF.

2.0 HISTORY OF COLD DWELL FATIGUE IN TITANIUM ALLOYS

The detrimental effects of CDF were first realized in late 1972 and then again in early 1973 when the IMI685 fan disk in Rolls Royce (RR) RB211 engines suffered catastrophic failure at a small fraction of the original design life, i.e. 335 and 279 flight cycles whereas prior rig tests showed no failure below 9,500 cycles (Bache, 2003). Subsequent investigation revealed that these failures were due to accelerated crack propagation from pre-existing flaws (Whitaker, 2011). To avoid further failure, the engines were required to be inspected every 50 cycles until a new fan disk from Ti-6Al-4V could be qualified and produced to replace the suspect engines. Quite amazingly, this took only about one year from the date of failure (Ruffle, 1991). The choice for Ti-6Al-4V was based on the past successful experience of this alloy for fan disk applications. To this day it remains the alloy of choice for fan disks and for many years this alloy was considered to be “insensitive” to CDF, however, recent events have changed the titanium industry’s view on this as will be discussed in more detail below. These failures also spawned a flurry of research activity in the United Kingdom that soon spread to the United States. Collectively, these investigations revealed that the CDF mechanism was very complex with dependence on alloy composition (including interstitials), microstructure, texture, applied stress, and temperature. Because of these interactions, and strong volume-dependence of the mechanism (Song, 1989), there were often conflicting results in the literature. For example, some investigators finding crack growth rates were accelerated, others found reduced crack growth rates, while others still found no effect at all (Bache, 2003; McBagonluri, 2005; Evans, 1979; Chesnutt, 1979; Sommer, 1983; Shen, 2004). The confusion, ultimately, was because of many interrelated factors of the microstructure, texture, and microtexture that were not easy to rigorously quantify at the time. Despite the conflicts, it is known that dwell fatigue gets worse at higher applied max stresses and also with increasing temperature up to ~120 ^{o}C (for Ti-6242 (Zheng, 2017)) and then diminishing completely above ~200 ^{o}C (Winstone, 1984). There is a strong dependence of both macrotexture (Woodfield, 1998) and microtexture (Woodfield, 1995 and 1998) with elastically compliant and low strength conditions (i.e. deforming primarily by prismatic <a> slip) exhibiting longer lifetimes, higher strain-to-failure, and limited-to-no facet formation at the nucleation sites. These early efforts paved the way, however, for the modern-day understanding. They illustrated the now-characteristic subsurface, faceted crack nucleation sites with spatial orientations nearly perpendicular to the applied stress (Evans, 1987), which resulted in the first notion that local anisotropy and time-dependent stress redistribution within the material might be responsible for early crack nucleation (Evans, 1995).

Around the same time, General Electric began to experience a series of failures of their CF6 engines. Some of these were attributed to hard-alpha (a melt-related, nitrogen-stabilized anomaly) while others were attributed to CDF (Garvey, 1998). The fracture surfaces exhibited faceted areas much larger than the underlying microstructural unit size and hence a study was undertaken to use the recently commercialized electron backscatter diffraction (EBSD) technique to determine the grain orientations in the vicinity of a subsurface CDF crack (Woodfield, 1995; Woodfield, 1998). These efforts revealed large regions of crystallographically aligned primary alpha which measuring hundreds of micrometres to several millimetres. These features, now called microtextured regions (MTRs) or macrozones, were remnants from the large, aligned alpha-colonies present during conversion from ingot to billet. They form as a result of a geometric recrystallization process whereby the crystallographically equivalent laths are fragmented into smaller particles by dislocation motion and short-range diffusion during hotworking and subsequent heat treatment. Because of the similar initial orientation and anisotropy in slip system strengths, all particles tend to rotate the same way and hence retain a similar orientation in the final forging. The low-angle boundaries between adjacent grains within the MTRs offer an easy pathway for transgranular crack propagation, leading to the large, shiny, faceted features reported on CDF fracture surfaces.

During the time of the CF6 failures, Jim Williams was the General Manager of GE Aviation's Materials, Processes, and Engineering Division. In 1999, he left GE and became a faculty member at The Ohio State University. Here, he formed a team of experts to investigate the fundamentals of CDF failure under a large program from the Federal Aviation Administration. The team, consisting of experimentalists, microscopists, modelers, and nondestructive evaluation (NDE) specialists, was charged with understanding the fundamental factors contributing to early CDF failure, using this to build mechanism-based micromechanical models, and develop NDE methods to assess the degree of microtexture in forged titanium. The ~10-year program, which ended ~2010, contributed significantly to the basic scientific understanding of the failure mechanism (Ghosh, 2007; Mills, 2018). An important foundation for a fatigue crack nucleation model was also developed at this time by Prof. Somnath Ghosh's group. The model featured elastic and plastic anisotropy, time-dependent stress redistribution, a non-local crack nucleation criterion, wavelet-based time-scaling method, which enabled simluations to run for a realistic number of cycles to failure (e.g. 10's to hundreds of thousands). The present author was one of Prof. Williams' students who graduated around that same time and carried the torch, so to speak, to AFRL to continue investigating dwell fatigue behavior. Over the next several years, the AFRL team investigated the effects of microstructure and texture on small crack growth rates (Pilchak, 2014, 2015) and also investigated the role of temperature on dwell fatigue response of Ti-6Al-4V. Under the auspices of the Metals Affordability Initiative, AFRL also executed a significant amount of research related to dwell fatigue, which included developing machine learning models for processing-structure-property correlations, advancing the nondestructive evaluation methods, and maturing crystal plasticity finite element models (CPFEM) for dwell fatigue failure. In this regard, major enhancements were made to the Ghosh group code, which included a probabilistic fatigue crack nucleation criterion (Oztur, 2017) along with a hierarchical length-scaling enabled by using the output of many CPFEM runs to train machine learning algorithms about the effect of microstructural parameters on response (Kotha, 2019). These so-called parametrically homogenized constitutive models (PHCM's) are a hugely important advancement toward the practical use of CPFEM in design and lifing. When coupled with the aforementioned time-scaling, the latter modification gives one the ability to perform micromechanical models at every integration point on a full-scale component finite element mesh. This is a significant improvement over the linear elastic or non-linear elastic analyses often used today to design such components.

Meanwhile, the EPSRC's HexMat programme, which began in 2013, was well underway. This programme was a consortium of three universities (Imperial College, University of Oxford, and the University of Manchester) with industry partners from aerospace, nuclear, and defence industries (Rolls-Royce, TIMET, Westinghouse, and EDF). The programme complemented the US initiatives which, due to shifts in funding priorities, had begun to focus on moving up in length scale, by continuing to focus on the fundamentals of deformation behaviour of hexagonal material across time and space. Coupling of dislocation-dynamics with CPFEM by Dunne's group provided great insight into the effects of microstructure on the temperature-dependence of rate sensitivity (Zhang, 2015), which has implications on the ability to develop the dislocation pileups needed for load shedding and early nucleation. Britton's group continued advancement of micromechanical testing methods, high-resolution EBSD, and synchrotron x-ray techniques to study localized deformation and stress fields due to dislocation pileups (Britton, 2015; Guo, 2015; Jun, 2016a). The team also focused extensively on rate-sensitivity using in-situ micropillar (Jun 2016b), micro-cantilever, and nanoindentation (Jun, 2016c) tests. Because of the strong tension-compression asymmetry in titanium, these tests complemented the earlier work by May (May, 2010) who reported slip-system-specific under tension of millimeter-scale tension experiments.

There were also many other important characterization, modelling, and simulation advances under the HexMat Programme. For example, (Kartal, 2014) investigated the effect of crystallographic orientation and grain morphology on near-crack-tip-plasticity and crack-tip stress state, which provides some insight into the reason why certain 'hard-oriented' grains tend to undergo faceting. Lunt et al. continued to develop high resolution digital image correlation techniques (HR-DIC) to understand the deformation behaviour (Lunt, 2017) within MTRs and the role of alpha-2 precipitates. Meanwhile, the nondestructive evaluation team, led by Mike Lowe, used the finite element method to study the role of crystallographic orientation on the propagation of ultrasonic waves in heterogeneous microstructures (Lan, 2014). Their work culminated in the development of a method to recover the first few coefficients of the generalized spherical harmonics and to plot a (0001) pole figure solely from ultrasonic data (Lan, 2015). This is a huge advancement, though additional work is needed to increase the technical readiness level of this technology to make it applicable to the complex geometries and varying thicknesses of aeroengine components. Additional papers published as a result of the HexMat programme can be found on the internet (HexMat).

More recently, in 2017, a fan disk was liberated from one of the engines on Air France Flight 66 over Greenland. The plane landed safely, but without any of the fan disk remaining in the engine, the event was initially believed to be due to a manufacturing defect. Through persistent searching, a fragment was located by the BEA in 2019. A subsequent investigation by the Engine Alliance revealed subsurface crack nucleation with extensive faceted crack propagation in a large microtextured region (BEA, 2020). This fan disk was manufactured from Ti-6Al-4V and thus, this was the first documented commercial dwell fatigue incident for this alloy. This has enormous implications on the industry since Ti-6Al-4V is the workhorse alloy. Fortunately, Ti-6Al-4V components around the globe have logged billions of successful flight hours and hence there are clearly some nuances to this particular event that need additional investigation, but it represents an important turning point in the community's understanding of susceptibility to cold dwell fatigue.

3.0 MICROMECHANISMS OF DWELL FATIGUE FRACTURE

While Ti alloys exhibit high 0.2% offset yield strength under quasi-static testing conditions, micromechanical effects due to critical resolved shear stress anisotropy of the slip systems in the hexagonal-close-packed alpha-phase results in certain grain orientations having low yield strength which results in creep deformation during sustained loads at low temperature. Upon plastically deforming, these so-called "soft grains" shed their load to the neighbouring grains. If the neighbour is in a difficult-to-deform orientation (a "hard grain"), its stress continues to rise with increasing cycle count and hold time until the degree of plasticity is sufficient to nucleate a crack at the hard/soft grain interface (Pilchak, 2011). Once initiated, crack propagation occurs through a transgranular faceted growth mechanism that exhibits very limited and highly localized plastic deformation. Transmission electron microscopy investigations (Pilchak, 2012) reveal that continuous crack extension during the hold at peak stress likely occurs as a result of generation and propagation of <c+a> dislocations from the crack tip. The crack growth rates are so fast through these orientations because of the high CRSS of the pyramidal <c+a> slip systems which reduces plastic flow around the crack tip helping it remain sharp. The fracture surfaces of dwell fatigue specimens greatly resemble the fracture surfaces of Ti alloys fractured in hydrogen gas and hence it is highly probable that the hydrogen enhanced localized plasticity (HELP) mechanism (Shi, 1988) facilitates crack propagation as discussed in (Pilchak, 2011). This hypothesis was later supported by the work of Kirchheim et al. (Kirchheim, 2015), who discussed the chemomechanical effects of dissolved hydrogen in metals. Specifically, the authors describe how hydrogen makes it more thermodynamically favourable to generate dislocations at the crack tip, lowers the stress required to move them, and lowers the work-to-fracture to create new surfaces. These aspects result in rapid crack extension with very little energy absorption. X-ray tomography results coupled with post-test sectioning and electron backscatter diffraction (EBSD) analysis suggest that the cracks grow rapidly up to in near-alpha Ti alloys (Sinha, 2006; Pilchak, 2011). Observations of fracture surfaces and measurements of crack growth rates in Ti-6Al-4V, on the other hand, are not so conclusive and suggest nuances to the crack growth mechanism that warrant further investigation.

4.0 DESIGN AND SUSTAINMENT CONSIDERATIONS FOR COLD DWELL FATIGUE

Failure due to CDF is fortunately rare with only a handful of examples of commercial incidents in the public domain, but there are other known examples lurking in the depths of industrial knowledge. Moreover, because the use of EBSD and quantitative tilt fractography as a diagnostic tool for confirming dwell fatigue failure was only realized in 2006, the authors can’t help but wonder how many failures were misdiagnosed as simply “low cycle fatigue” throughout history. Nevertheless, this remains an important failure mechanism against which to safeguard in design and sustainment strategies for both military and commercial engines. To this end, one can apply the safe-life philosophy in which a series of specimen tests and components tests are performed to establish safe-operating conditions. Such an approach may provide a false sense of security since CDF is a weakest-link phenomenon and it is a near-statistical impossibility to obtain the worst-case microstructure in a test article. As a result, companies like Rolls Royce are fabricating test specimens incorporating the worst-case microstructure by diffusion bonding strongly textured plates (Xu, 2020) in order to establish a safe lower bound.

Deterministic or probabilistic damage tolerance provides an alternate approach to managing CDF. Because CDF may lead to a large debit on initiation life, one can assume a small flaw is present out of manufacturing which begins to propagate on cycle 1. The transgranular faceted initiation sites observed via fractography indicate that the primary alpha grain size distribution is a suitable distribution of initial crack sizes. Because the stress intensity factor range (ΔK) will fall below the threshold value for long crack growth, this approach requires one to consider the small crack effect as described in more detail below. Prior work has demonstrated that dwell fatigue cracks grow rapidly during the earliest stages when there is extensive facet formation (Ghosh, 2007; Pilchak, 2011; Pilchak, 2014; Pilchak, 2016).

Because of the strong volume dependence of CDF, and the fact that it is impractical to test all possible conditions, modelling and simulating have an important role. For the case of Ti alloys disks, which undergo low-temperature creep deformation and until detailed micromechanical models can be fully validated, it is recommended to use elastic-plastic finite element analysis which can account for stress redistribution on the component scale.

Regardless of the lifing philosophy, it is important to perform proper cycle counting. Typical commercial missions consisting of takeoff, cruise, and landing are often viewed as one cycle. The military missions, however, present a much greater challenge. While designed and lifed according to standard missions, no two planes fly the same and cycle and damage counting algorithms generally consider rotor speed crossings. Neither approach adequately considers the hold time effect for titanium alloys and it is recommended that all OEMs, certification authorities, and operators adopt new cycle counting strategies. This will require low-to-moderate TRL (technical readiness level) work. Furthermore, the likelihood of a particular component containing a rogue microstructural combination that will lead to early failure depends on its prior processing and also its stress level. Large commercial disks in high bypass ratio engines are generally forged from large diameter billets and thus typically contains larger MTRs (Pilchak, 2016b), but they operate at lower stresses making it less likely to “activate” the rogue combination. Military disks, on the other hand, are forged from smaller billets and thus should contain overall smaller MTRs, however, these tend to run at high stresses which may “excite” MTR’s that otherwise wouldsn’t be activated at lower stress. Modeling and simulation will be important in determining the critical conditions.

5.0 OUTLOOK

There is an enormous body of literature surrounding this highly complex and, fortunately, rarely occurring mechanism. The underlying root cause of dwell fatigue failure is undoubtedly related to micromechanical processes which are not captured with the continuum scale analyses used to design and life parts. The volumetric dependence and the need to get the critical combinations of grains together makes it very difficult to study in a laboratory. The community has been talking about the two-grain, hard-soft model for nearly 40 years. Such configurations are not rare and hence there are longer wavelength correlations that are important and which have gone undiscovered to date. This may include details of the internal structure of the initiating MTRs as well as many of the surrounding MTRs which provide the path by which the remote boundary conditions are transferred to the critical MTRs (i.e. the load path).

The only way to make progress is to increase communication among the community regarding component behaviour and to get teams working on common materials. The microstructure of titanium alloys is the summation of the composition and all prior processing steps, including billet-to-ingot conversion, finish forging, solution heat treatment and cooling. There are decades of examples of academia receiving some chunk of material without the context or background information. They characterize it, run a few dwell tests, and report similar results to what others have published. In a time where it’s already tough to get funding for basic metals research, this is not a good modus operandi. If industry is serious about solving this dwell fatigue problem, it is time to become more open with sharing information among the bright minds that are sitting in universities that are eager to work on something meaningful, important, and on which they can really make a difference. In addition, academic characterization groups need to get their hands on TEM foils from critical nucleation sites, CPFEM modelers need accurate component geometries, boundary conditions, and thermal histories. Failure analysts need to adopt the latest tools to characterize microstructure, texture, and microtexture around component crack nucleation sites and then make them available to the academic community. Open access to data is needed and the Defence Science Technology Group (DSTG) in Australia has made great headway on this for airframe structural applications through their ASSIST (Advancing Structural Simulation to drive Innovation Sustainment Technologies) effort (Dixon, 2019). ASSIST makes available information about real structural failures so that various groups can apply their models to that situation to improve their predictive ability. Fortunately, there is precendence for this type of close collaboration in the titanium industry already, which was born out of necessity following the 1989 crash of a DC-10 in Sioux City, Iowa due to the presence of a melt-related defect known as “hard alpha.” In this case, industry partnered closely with academics at Iowa State University’s Center for Nondestructive Evaluation (CNDE) in an effort . An industrial group organized under the auspices of the Federal Aviation Administration known as the Jet Engine Titanium Quality Consortium (JETQC) continues to meet regularly to share information related to this most deleterious defect as it is a safety concern. This same group can be the nucleus for a new close collaboration with industry on the next most pressing safety concern for titanium alloys, i.e. MTRs.

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