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Cold Dwell Fatigue of Titanium Alloys

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It has been about 50 years since the discovery that titanium alloys were susceptible to a phenomenon known as cold dwell fatigue (CDF), following two in-service failures of the Rolls Royce RB211 engine. Since then, a plethora of academic, industrial, and government research has been performed to understand the major factors influencing CDF. This work has demonstrated that CDF failures have a few unique characteristics, namely, cracks nucleate early and often at subsurface locations, which exhibit large, faceted initiation sites,[1] and cracks can grow at alarmingly fast rates during the early stages of growth.[2] The size of the individual facets are commensurate with the alpha particle size in alpha + beta worked material[3] and the alpha colony size in beta-processed materials. The size and shape of the faceted initiation sites closely mirrors the size and shape of the underlying microtextured regions (MTRs) or macrozones in the material. MTRs are large aggregates of similarly oriented alpha-phase, which originate during conversion of titanium ingot to billets, and may persist through forging and solution heat treatment. Because titanium is elastically and plastically anisotropic, some MTRs deform preferentially, which can have a severe impact on secondary processing,[4] as well as on CDF behavior,[5] and increase noise during ultrasonic inspection, making it difficult to detect defects.[6] The major factors that influence CDF include: (1) alloy composition,[7] (2) microstructural condition,[8] (3) duty cycle including stress and temperature,[9] (4) stress state,[10] (5) stressed volume of material,[11] and (6) bulk residual stresses from the manufacturing process. Sophisticated computational models have been developed to aid in understanding the impact of microstructural features, anisotropy, temperature dependence, and rate sensitivity on dwell fatigue capability.[12,13]

Despite such detailed understanding, CDF remains an important problem affecting the safety and reliability of civil aircraft today. There were a series of failures of GE's CF-6 engines in the 1990s, which impacted compressor spools made of Ti-6Al-2Sn-4Zr-2Mo; see Ref. 14 for example. Until this point, CDF had only impacted alloys like IMI-829, IMI-834, and Ti-6242, and hence it was believed that the issue was isolated to the near-alpha class of alloys. More recently, however, the fan disk on the number four engine of Air France Flight 66 departed the aircraft at cruising altitude over Greenland in a widely reported news story. An extensive search effort was conducted to find the missing disk fragment, which was summarized in the BEA's report on the topic, and a short video was also released on YouTube.[15,16] The subsequent failure investigation performed by Pratt and Whitney revealed a subsurface origin surrounded by extensive faceted growth. Sectioning into the fracture surface and performing electron backscatter diffraction analysis beneath the origin revealed the characteristic MTR. This was an important event, in that it showed for the first time that the industry workhorse alloy, Ti-6Al-4 V, which comprises the major fraction of titanium used in the aerospace industry, was not immune to CDF when operated at engine-relevant stress levels, as previously suspected.

In light of these recent developments, the TMS Titanium Committee has convened this special topic on the CDF of titanium alloys for this issue of *JOM*. We solicited papers covering all aspects of CDF, ranging from processing/microstructural effects on CDF, anisotropy and texture, impact of CDF on material performance, nondestructive evaluation methods for characterizing MTRs, and modeling and simulation, among others. Homa et al. have made progress toward using eddy current inspection technology to estimate MTR orientation

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distribution functions by leveraging the anisotropic conductivity of HCP titanium. In the future, as the industry shifts toward serial-number-based lifing methods, techniques like this will be instrumental in identifying fielded components that may be more susceptible to CDF. Wendorf et al. have used modeling and simulation to investigate the role of grain-scale stress states within microtextured regions of Ti-6Al-4V. Using a directional strength-to-stiffness criteria, the authors show that moderately misoriented grains within hard-oriented MTRs are preferential sites for early yielding. This provides a theoretical basis for the recent observations of Harr et al.,[17] who demonstrated that grains well aligned for basal slip within otherwise hard-oriented MTRs were preferential sites for the development of long-range slip bands. MTRs are complex, three-dimensional features, yet we often only have the resources to observe them on two-dimensional planes. James et al. have applied a stereological 'unfolding' algorithm to estimate the 3D MTR size distribution from 2D measurements, assuming that the MTRs can be described by prolate spheroids. The impact of using 2D versus 3D measurements on MTR-sensitive damage tolerance lifetime are discussed. You et al. have performed a detailed characterization of IMI-834 dwell fatigue samples extracted from a disk forging, using scanning and transmission electron microscopy as well as x-ray computed tomography and electron backscatter diffraction. This article has been selected as Editor's Choice for Open Access. Ziaja and Kawalec[18] have reported on the dwell capability of two different Ti-6Al-4 V microstructures at elevated temperatures. In contrast to the near-alpha class of alloys, for which room temperature dwell tests seems to be a good method of assessing sensitivity, moderately elevated temperature testing in the range $100 \sim 200$ °C, which are engine-relevant operating conditions, tends to exacerbate the Ti-6Al-4 V alloy. These papers have been paired by the editorial office with a few others on titanium alloys submitted to *JOM* around the same time, to round out this month's special issue. Finally, it is worth noting that the 15th World Conference on Titanium, held quadrennially, will occur in Edinburgh, Scotland, 12–16 June 2023.

All titles and authors of the articles published under the topic "Cold Dwell Fatigue of Titanium Alloys" in the October 2022 issue (vol. 74, no. 10) of *JOM* can be accessed via the journal's page at: http://link.springer.com/journal/11837/74/10/page/1.

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