ABSTRACT

The present study aims to develop a comprehensive understanding of the thermomechanical fatigue (TMF) behaviour of two structural alloys widely employed in aero-engine applications: the titanium-based Timetal 834 alloy and the nickel-based directionally solidified (DS) CM247LC superalloy. The investigation systematically examines the effects of temperature range, strain amplitude and phase angle on cyclic stress response, fatigue life, microstructural evolution, and fatigue damage mechanisms under various strain-controlled TMF loading configurations in both the alloys. Towards this, the TMF experiments on Timetal 834 alloy were performed under clockwise diamond (CD) and counterclockwise diamond (CCD) loading conditions at the strain amplitude of $\Delta\varepsilon_m/2$ = ±0.6% and ±1.0% over two temperature intervals, 573 K↔723 K and 723 K↔873 K. Post-TMF tests, the microstructural characterization of the failed specimens was carried out using scanning electron microscope (SEM), electron backscatter diffraction (EBSD) and transmission electron microscope (TEM) techniques. The TMF test results demonstrate that fatigue life in Timetal 834 alloy is governed by the complex interplay among phase angle, strain amplitude and temperature range. In the higher temperature interval (i.e., 723 K↔873 K), the alloy exhibits a shorter fatigue life under CCD conditions than under CD ones, primarily due to pronounced oxidation-induced damage, as revealed by fractographic analyses. Conversely, in the intermediate temperature range (i.e., 573 K↔723 K), fatigue life is reduced under CD condition compared to CCD one at a given strain amplitude, owing to the accumulation of greater tensile damage during each cycle. The kernel average misorientation (KAM) analyses reveal that strain localization is more pronounced under CD condition than CCD one at a given strain amplitude in this temperature range. EBSD analyses further show the development of band-like structure inside the primary alpha (α_p) grains where strain localization is substantially greater in both CD and CCD conditions. TEM observations corroborate these findings and reveal dense dislocation density at the concavities around α_p grain boundaries. The fractography studies show faceted α_p grains near the crack initiation sites. The EBSD analyses reveal that these facets are interrelated to strain localization in α_p grains, oriented along basal or prismatic with high Schmid factor. In contrast to the Timetal 834 alloy, the TMF behaviour of the DS CM247LC superalloy was investigated under in-phase (IP), out-of-phase (OP), CD, and CCD loading conditions over a much wider temperature range (i.e., 573 K↔1143 K) at the strain amplitudes of $\Delta\varepsilon_m/2$ = ±0.5% and ±0.8%. The results reveal that TMF life in DS CM247LC superalloy is strongly influenced by the dominance among the creep, fatigue and oxidation. Under IP condition, the fatigue life of DS CM247LC superalloy is significantly reduced due to the synergistic effect of creep-fatigue-oxidation damage, especially at high strain amplitude. Conversely, under OP condition, fatigue life degrades due to oxidation-fatigue damage and the formation of micro-twins, specifically at high strain amplitude. The cyclic stress response under IP condition is characterized by initial hardening followed by softening, whereas continuous hardening is observed before failure under OP condition. Initial hardening in both IP and OP-TMF conditions is attributed to dislocation-dislocation and dislocation-precipitate interactions. The subsequent softening phenomena under IP condition arises due to shearing of γ' precipitates by stacking faults and anti-phase boundary, whereas the hardening phenomena under OP condition is associated with micro-twins, especially at high strain amplitude. In comparison with IP and OP loading scenarios, the alloy DS CM247LC subjected to CD and CCD conditions exhibits enhanced fatigue life at the same strain amplitude. However, between the CD and CCD loading scenarios, the TMF results demonstrate that CCD-TMF leads to a shorter fatigue life than CD-TMF, primarily due to a greater oxidation-fatigue induced damage. EBSD-KAM analysis corroborates this behavior by revealing more pronounced strain localization under CCD condition than CD one at the same strain amplitude. Consistent with these observations, fractographic analysis reveals substantially greater oxidation-induced damage under CCD condition, accounting for the inferior fatigue performance, which is driven by the tensile stress acting in the high-temperature regime. At the low strain amplitude (i.e., $\Delta\varepsilon_m/2$ = ±0.5%), the alloy exhibits a stabilized cyclic stress response under both CD and CCD conditions, resulting from a balance between hardening phenomena, attributed to interaction among dislocations and γ' precipitates and softening phenomena, arising from the shearing of γ' precipitates by slip bands. At a higher strain amplitude (i.e., $\Delta\varepsilon_m/2$ = ±0.8%), mild softening dominates under CD condition due to shearing of γ' precipitates, whereas a stabilized stress response is maintained under CCD condition, primarily due to formation of Lomer-Cottrell locks. Across all the TMF conditions, a high dislocation density is commonly observed near MC carbides in DS CM247LC superalloy, as evidenced by TEM analyses. Fractography analysis substantiates these observations and shows numerous micro-cracks near MC carbides.

***Keywords*:** Clockwise diamond; Counterclockwise diamond; CM247LC superalloy; Deformation behavior; Dislocation; Facet; Fatigue-oxidation-creep; In-phase; Out-of-phase; Oxidation-fatigue damage; Phase angle; Slip bands; Stacking faults; Strain localization; Thermomechanical fatigue; Timetal 834 alloy.