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Project Title

Multi-scale experimental study of creep-fatigue failure initiation in a 709 Stainless Steel alloy using high resolution digital image correlation

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ABSTRACT:

Metal fatigue and metal creep have been separately well studied over the past century. However, although for most advanced structures undergoing thermo-mechanical fatigue (e.g., nuclear reactors, hypersonic aircraft, aero-engines, etc.) both mechanisms are synergistically coupled, the damage rules used so far to relate them have been confined to linear superposition in most cases. Critical issues such as the interaction of thermal and mechanical cycling, or coupling of thermal and mechanical failure modes, have not been thoroughly understood. In addition, as the operating temperatures increase and/or the exposure times are prolonged, the combined influence of creep damage and fatigue damage increases but the details of how this takes place are unknown. **Our goal in this effort is to perform reliable and efficient experimental studies of creep-fatigue response over a range of relevant material length scales**, and to incorporate these experimental results in **a predictive modeling framework** for the long term failure prognosis in such extreme coupled environments.

The material to be studied will be Stainless Steel Alloy 709 which is an austenitic alloy that has been down-selected by DOE for possible use in sodium fast reactor applications. Although a number of studies have been conducted to determine the response of 709 under a variety of thermo-mechanical loading conditions, little information is available on the deformation mechanisms of this material at a microstructural size scale under fatigue-creep conditions. The material microstructure demonstrates significant precipitates both at the grain boundaries and in the grain interiors which are areas of concern as thermo-mechanical fatigue initiation sites in addition to the grain boundaries themselves.

The proposed project will concentrate on the detailed experimental investigation of creep-fatigue response in the 709 alloy under a wide range of loading and temperature conditions. As cyclic mechanical and thermal loading evolves, plastic strain accumulates at the microstructural level and eventually leads to formation of fatigue microcracks. The focus of this work will be on three aspects of this process: (i) multi-scale experimental study of plastic strain accumulation with special emphasis in identifying the interaction of factors that affect plastic strain development, (ii) experimental identification and assessment of microcrack formation both on the surface and in the interior of the material, and (iii) use of the experimental findings in a predictive failure initiation model that includes both thermo-mechanical and aging effects. In our effort "creep-fatigue" is defined as thermo-mechanical fatigue (TMF) loading that is interspersed with long hold periods during which both TMF and creep mechanisms may be active.

The experiments in (i) and (ii) will use real-time in situ and/or ultra-high resolution ex situ digital image correlation (DIC) to measure the accumulation of plastic strain over long periods of cycling, and at three physical length scales: the material micro-scale (i.e., the single grain and sub-grain level), the meso-scale (i.e., a collection of several grains that may exhibit cooperative behavior), and the macro-scale or specimen scale (i.e., a very large number of grains over the entire sample). DIC is an optical technique

which provides direct measurement of full-field displacement and strain on the surface of a material by tracking the motion of a random speckle pattern before and after deformation. In the past we have developed an ultra-high resolution DIC in which a rastering of images are stitched together to form an ultra-high resolution measurement that incorporates measurement points every 1-5 μm. Such ultra-high resolution DIC measurements are capable of resolving strain accumulation along individual Persistent Slip Bands (PSBs) within a grain. Thus the ultra-high resolution DIC allows for assessment of both plasticity and damage accumulation within specific grains while *at the same time* investigating collective grain plastic response and grain boundary effects.

Hourglass-shaped samples specifically designed to promote damage in the central area will be used, thus limiting the area of coverage that must be monitored. The starting, evolving, and ending microstructure will also be monitored using EBSD measurements. The proposed experiments will be conducted at elevated temperature using induction heating of the sample. The experimental plan will cover a range of TMF loading conditions, and stress and strain control isothermal experiments in order to investigate whether thermal creep and fatigue damage in 709 can be treated in an additive fashion, as has been done in the limited cases to date, or if in fact, as is most likely the case, the two are related in a nonlinear path-dependent fashion. Additionally, we will perform fatigue-creep experiments with long holding times and at varying levels of temperature and amount of holding time to elucidate the microstructural effects associated with long term exposure to temperature while under fatigue loading. Of special importance in this context will be identifying similarities/differences between microstructural localization modes at various temperatures, so that the premise of accelerated aging experiments (i.e., studying the alloy at higher temperatures than operating, but for shorter times) can be validated.

From the high resolution deformation measurements, we will statistically establish a damage distribution (i.e., of microcracks) on the surface and relate that to the DIC strain distribution measured in the material. This method has shown significant promise in earlier studies we have conducted on the thermo-mechanical fatigue of nickel-based superalloys. Here by utilizing multiple cameras we will precisely establish in addition the-out-of-plane displacements. Sub-surface damage assessment will then be undertaken by the novel combination of DIC measurements with enrichment functions which are in essence a way to solve an inverse problem to determine sub-surface damage based on perturbations visualized on the recorded displacement field on the surface. The feasibility of this non-destructive damage assessment process will also be confirmed by some (destructive) serial sectioning experiments. This approach will shed light into the propensity of creep-dominated damage that could develop sub-surface. Finally, a closely coupled modeling effort will extend our existing slip band-based energy minimization criterion for predicting fatigue crack initiation to include thermal effects, and to include the effects of the precipitates present in the 709 microstructure. The model is based on PSBs reaching a critical energy level before a crack initiates and is therefore very physically based. DIC will provide a wealth of microstructural strain information that cannot be obtained accurately otherwise, thus allowing a much more accurate computation of the PSB energy and a better prediction of both when and where failure would initiate.

This work will concentrate on combined creep and fatigue loading, as opposed to solely creep. The effort will be primarily experimental in nature and will provide one of the most detailed datasets of full-field strain measurements at both the collective grain and the sub-grain levels. As such it will be suitable both for understanding in detail how damage forms and progresses at the micro-scale, and also for validating multi-scale simulation results. The modeling effort will take the existing and very physically based slip band energy minimization model that the PIs have developed in the past, and modify it appropriately to incorporate the additional physical features of the 709 material (precipitates, long term aging, etc.). The major deliverables and outcomes the R&D will produce: (i) an understanding of grain-level strain evolution in 709; (ii) a multi-scale model for combined fatigue and fatigue-creep crack nucleation prediction; (iii) a database of coupled thermal and mechanical loading response of 709, (iv) detailed validation-quality strain mapping evolution of damage in the grain structure of 709.