VISCOELASTOPLASTIC DEFORMATION AND DAMAGE RESPONSE OF TITANIUM ALLOY, TI-6AL-4V, AT ELEVATED TEMPERATURES

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ABSTRACT: Time-dependent deformation and damage behavior can significantly affect the life of aerospace propulsion components. Consequently, one needs an accurate constitutive model that can represent both reversible and irreversible behavior under multiaxial loading conditions. This paper details the characterization and utilization of a multi-mechanism constitutive model of the GVIPS class (Generalized Viscoplastic with Potential Structure) that has been extended to describe the viscoelastoplastic deformation and damage of the titanium alloy Ti-6Al-4V. Associated material constants were characterized at five elevated temperatures where viscoelastoplastic behavior was observed, and at three elevated temperatures where damage (of both the stiffness reduction and strength reduction type) was incurred. Experimental data from a wide variety of uniaxial load cases were used to correlate and validate the proposed GVIPS model. Presented are the optimized material parameters, and the viscoelastoplastic deformation and damage responses at the various temperatures.

INTRODUCTION: The GVIPS (Generalized Viscoplasticity with Potential Structure) model is a comprehensive viscoelastoplastic constitutive model that aims to describe a material's behavior whether in the viscoelastic or viscoplastic region (Saleeb et al. 2001 and Saleeb and Arnold, 2004). Previous studies involving the titanium alloy TIMETAL 21S have shown the robustness of this model. Herein the model is employed to characterize the tensile, creep, relaxation, cyclic, and thermal recovery deformation behavior of Ti-6Al-4V over a wide range of elevated temperatures, i.e. at 600°F, 700°F, 800°F, 900°F, and 1000°F. An optimal set of multi-mechanism viscoelastoplastic model parameters were obtained, for each temperature, using the fully-automated, material parameter estimator, COMPARE [Saleeb et al. 2004]. More recently, the GVIPS model was extended to include softening due to stiffness and/or strength-reduction damage mechanisms (Saleeb and Wilt, 2005). It is this feature of the model, when linked with state-awareness capabilities, which will provide the required ability to compute the damage progression and ultimate life in a structure. A key finding of the present work is the demonstration that stiffness reduction damage mechanisms are dominate in this material system. The final outcome of this study is a complete set of viscoelastoplastic and damage material parameters characterized at each temperature.

PROCEDURES, RESULTS AND DISCUSSION:

Overall, titanium alloys demonstrate a full range of rate- and time-dependent material response over a wide stress and temperature range. The number of mechanisms required to accurately model the complexity of the material's response behavior under a variety of loading situations increases with temperature. First, the viscoelastic behavior was characterized for all stress states below the experimentally obtained threshold stress. At 600^{o}F this was accomplished with a single mechanism with a relaxation time of 21,082 sec, whereas at 700, 800 and 900-1000^{o}F it required 2, 3 and 4 mechanisms, respectively; with successively shorter associated relaxation times, that is 3,394, 290 and 56 seconds respective. Once the viscoelastic characterization is fixed, one can proceed to characterize the viscoplastic behavior using tensile, creep, and relaxation response curves like those shown in Figure 1, note the symbols represent experimental data points and the solid lines simulation response. In the viscoplastic region, that defined by stresses greater than the threshold stress at a given temperature, 2 viscoplastic mechanisms were required at 600^{o}F, while 3 viscoplastic mechanisms were employed between 700 and 900^{o}F, with 4 being required at 1000^{o}F.

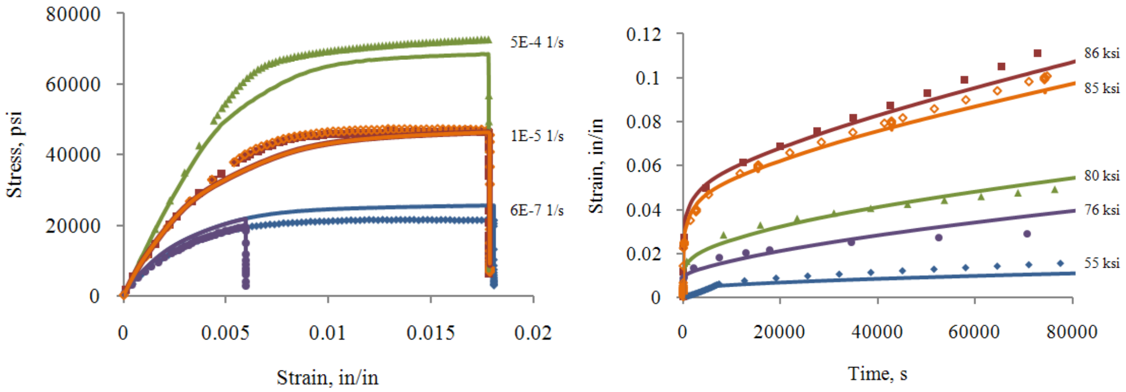

Figure 1: a) Tensile followed by relaxation tests at different total strain rates, 1000°F and b) creep tests at various stress levels at 800°F.

With the viscoelastic and viscoplastic deformation regions fully characterized, it became apparent from a number of intermittent unloading tests conducted (both tensile and creep), that softening mechanisms would need to be accounted for, most importantly those associated with stiffness reduction mechanisms. Figure 2 illustrates just such an interrupted tensile test at 1000^{o}F, wherein both experimental and two simulations, one without damage included and the other with damage (both stiffness and strength reduction, see Arnold et al (2009) for more details). Clearly, the simulation with no damage (dashed line) erroneously continues to climb to progressively higher stresses as strain increases, whereas that with damage (solid red line) more accurately portrays the experimental data. The need to include damage is more clearly seen when the loading modulus is plotted versus that of load cycle, as in Figure 2b, where it is apparent that the response when damage mechanisms (both stiffness and strength) are activated (square symbols) tracks with the rate of degradation of the overall loading modulus (diamond symbols) extremely well. When only the stiffness damage mechanism is activated, the actual magnitude of loading modulus can be matched more closely, however the rate of the degradation (slope) is far too severe. Further experiments have shown that similar stiffness reductions are achieved under creep loading conditions (when one compares loading modulus values at equivalent total strain magnitudes) it was similarly shown that tertiary creep rates were better simulated when both stiffness and strength degradation mechanisms were activated.

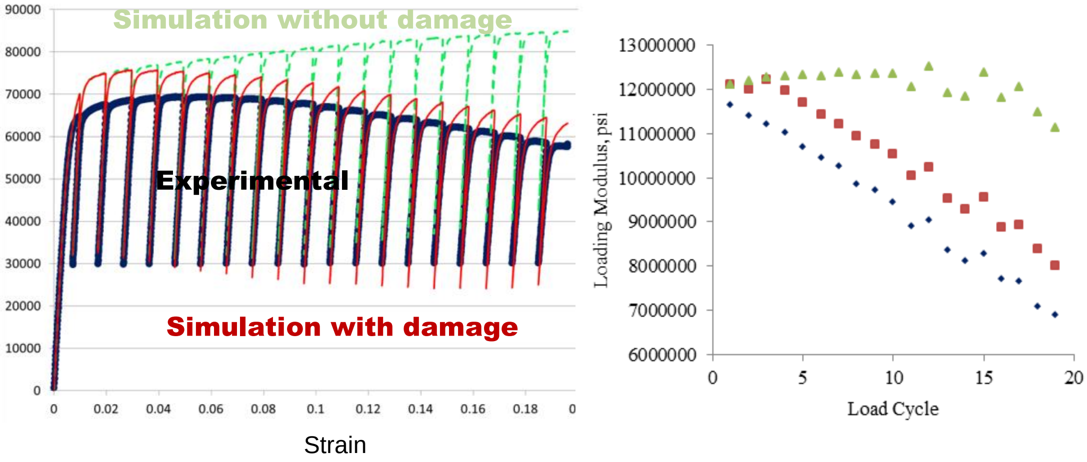

Figure 2: a) Tensile test and simulations (without (dashed line) and with damage (solid line)) with intermittent unloads at every 1 percent of total strain (1000°F), b) loading modulus (both real (diamond) and simulated (without (triangle) and with damage (square)) versus number of unloads

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