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Damage Evolution in Metal Matrix Composites Subjected to Thermomechanical Fatigue

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Abstract

A thermomechanical analysis of unidirectional continuous fiber metal matrix composites is presented. The analysis includes the effects of processing induced residual thermal stresses, interface cracking, and inelastic matrix behavior on damage evolution. Due to the complexity of the nonlinear effects, the analysis is performed computationally using the finite element method. The interface fracture is modeled by a nonlinear constitutive model. The problem formulation is summarized and results are presented for a four-ply unidirectional SCS-6/ß21S titanium composite under high temperature isothermal mechanical fatigue.

1. Introduction

In recent years, there has been great interest in Metal Matrix Composites (MMC's), in particular, the SiC/Ti alloy system. This interest is due to the fact that advanced applications have demonstrated a need for materials with high strength-to-weight ratios and an ability to retain mechanical integrity at relatively high temperatures. Components in these applications are often subjected to harsh environmental conditions, and stresses and temperatures that vary simultaneously.

Many studies have been reported on the behavior of the SiC/Ti alloy systems. A detailed literature search including research on most of the popular SiC/Ti alloy systems is given in a recent publication by Allen et al. (1994b). Most recently, a composite using the metastable Ti alloy called ß21S has been investigated because of its superior oxidation and corrosion resistance.

The general characterization of ß21S was performed by TIMET Henderson Technical Laboratory including the processability, and resistance to oxidation and corrosion (Smith and Revelos, 1992; Grauman and Mild, 1992; Bania and Parris, 1992). Neu (1993) has determined the

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material parameters for ß21S for use in a version of the Bodner-Partom model (Bodner, 1987), in order to model its high temperature viscoplastic behavior. Ghonem et al. (1993) have studied the effects of temperature and frequency on fatigue crack growth.

There have been several experimental studies performed on the isothermal and thermomechanical fatigue (TMF) behavior of SCS-6/ß21S composites, between the temperatures of 150°C to 650°C (Nicholas and Russ, 1993; Neu and Nicholas, 1994). The damage in the in-phase (IP) TMF and isothermal fatigue tests appeared to be fiber dominated; whereas, the out-of-phase (OP) TMF results showed matrix dominated damage.

2. Formulation

The problem of interest in this work is modeling the behavior of a four ply unidirectional ß21S MMC subjected to cool down from processing temperature, and subsequent isothermal fatigue. This research will include the effects of viscoplasticity in the matrix, fiber-matrix debonding and radial cracking. The temperature and load histories used in the current work are given in Fig. 1 and Fig. 2, respectively. A full description of the formulation of the necessary equations used in the analysis of this problem are not included due to space restrictions.

2.2 Finite Element Implementation

The finite element formulation is a result of all of the field equations being cast into a variational formulation and then discretized. This procedure is detailed in Allen et al. (1994a). The thermomechanical code used in this analysis is an in-house code called SADISTIC (Structural Analysis of Damage Induced Stresses in Thermo-Inelastic Composites). This algorithm requires extensive computational requirements due to the time stepping procedure necessary for integrating the viscoplastic constitutive equations.

2.2.1 Boundary Conditions and Meshes

The boundary conditions are shown on the Representative Volume Element (RVE) in Fig. 3. A multiple constraint condition is applied on the right face during cool down by the use of a penalty function as outlined in Cook (1989). The current results assume a spatially homogeneous temperature distribution and generalized plane strain conditions. All mesh elements are constant strain triangles except those at the fiber-matrix interface which are modeled using interface elements (Needleman, 1987).

3. Results and Discussion

The results of the thermomechanical analysis of the damage evolution of a four-ply unidirectional SCS-6/ß21S titanium composite under isothermal mechanical fatigue are presented and discussed below. Three separate cases are considered: 1) thermoelastic matrix behavior with interface cracking, 2) viscoplastic matrix behavior without interface cracking, and 3) viscoplastic matrix behavior with interface cracking. All three cases assume thermoelastic fiber behavior. Each case is computed for one cycle of uniaxial stress loading at a constant temperature of 482°C. Representing each considered case, Figs. 4, 5, and 6 show stress vs. strain compared to experimental data for isothermal fatigue loading applied in the fiber direction for the given loading and temperature histories. From the graphs, it is observed that the thermoviscoplastic case with damage compares the most favorably with the experimental data. The thermoelastic case fails to predict the observed time-dependent material behavior. The thermoviscoplastic case without damage fails to accurately predict unloading.

These preliminary results indicate that both nonlinear matrix behavior and the presence of interface cracking can be incorporated to more accurately predict the damage evolution in MMC's.

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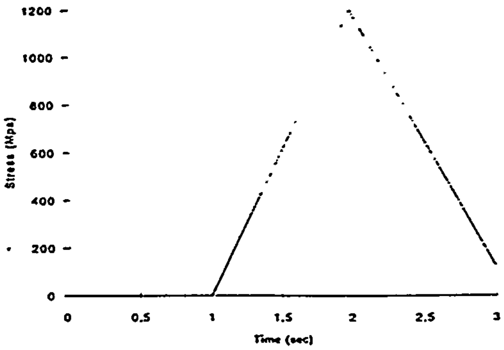

Figure 1. Load History

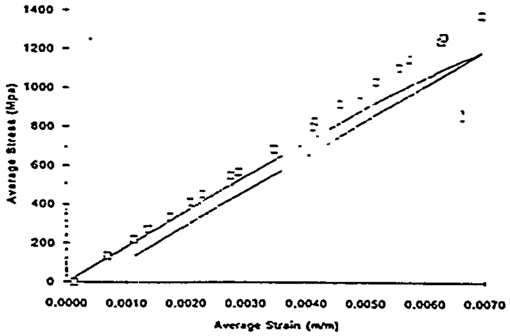

Figure 4. Thermoelastic with Damage

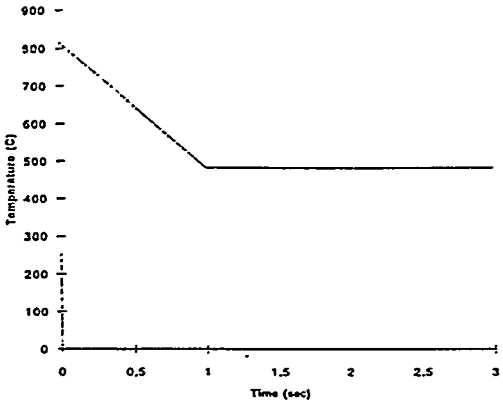

Figure 2. Temperature History

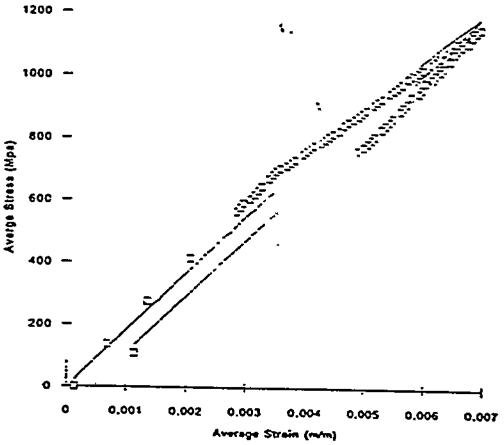

Figure 5. Thermoviscoplastic

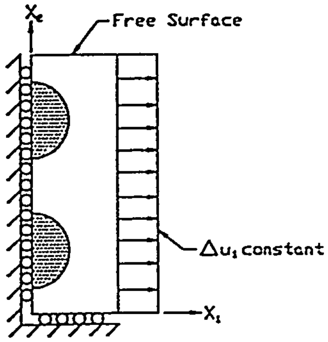

Figure 3. Representative Volume Element

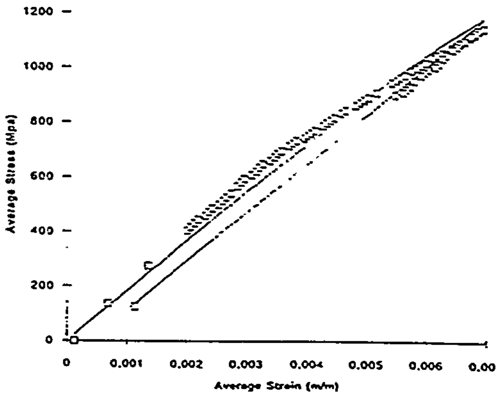

Figure 6. Thermoviscoplastic with Damage