MICROMECHANICAL MODELING OF HYBRID SMA COMPOSITES

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Summary A numerical model of a hybrid Shape Memory Alloy (SMA) - MAX phase ceramic composite is developed considering the effects of the different inelastic mechanisms present and the influence of the microstructure. The effective behavior of such a composite is explored and it is demonstrated that a residual stress state may be generated in the composite by using the unique inelastic mechanisms present.

INTRODUCTION AND MODELING METHODOLOGY

A new hybrid Shape Memory Alloy (SMA) - MAX phase ceramic hybrid composite is being developed for use in extreme environments. It is intended that by taking advantage the reversible martensitic transformation of the SMA phase [1] and unique kinking behavior of the MAX Phase [2] a compressive residual stress state is developed on the ceramic MAX phase which takes advantage of its superior mechanical response under compressive loadings. The effective transformation characteristics of the composite and its ability to generate the desired residual stress state are explored here. Specifically, a numerical model is developed which accounts for the different inelastic mechanisms present in the system as well as the effect of the irregular microstructure. Importantly, the heterogeneous microstructure generated through the manufacturing of these composites is accounted for by using a numerical mesh generated through x-ray tomography.

Modeling Methodology

To develop a model of the composite being investigated the distribution and constitutive behaviors of the phases must be defined. First, as the manufacturing process of the composite leads to a heterogeneous material, the microstructure of a co-sintered NiTi-Ti_2AlC, where NiTi is the SMA phase and Ti_2AlC is the MAX phase), is characterized through x-ray microtomography. The resultant tomographs are then segmented and turned in a finite element mesh. This process and the final mesh are shown schematically in Fig. 1. The final composite is composed of 40% Ti_2AlC and 30% NiTi with 30% porosity.

To describe the constitutive behavior of the NiTi phase, a recent 3D phenomenological constitutive model developed and

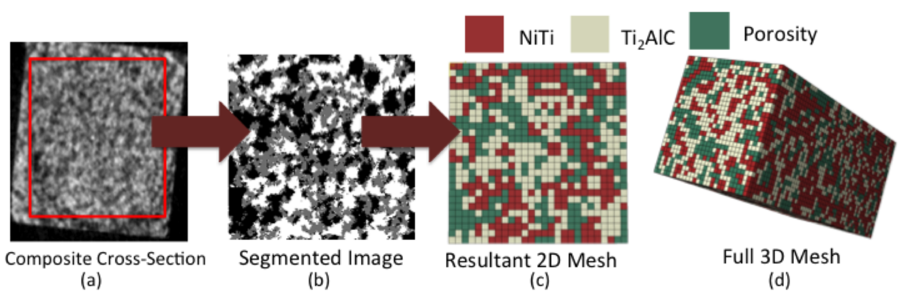

Figure 1. Numerical mesh generation of a NiTi- Ti_2AlC phase composite: (a) x-ray tomograph of a cross-section of the considered composite (b) segmented image of the cross-section (c) the reduced finite element mesh of the cross-section and (d) the final, full 3D mesh

implemented as an ABAQUS user material subroutine by Lagoudas and colleagues [3] is used. To describe the MAX phase response, however, an elasto-plastic approximation is utilized due to the lack of an existing 3D phenomenological model describing the unique formation of both recoverable and irrecoverable kink bands in the material. Specifically, as the mechanism under investigations is the irrecoverable strain generation associated with kink band formation ABAQUS' isotropic hardening elasto-plastic model is fit as an approximation of the behavior. Interestingly, and unlike other ceramics, the kink band formation present results in the MAX phases being damage tolerant [2]. Using the above described numerical mesh and constitutive descriptions, the composite is subjected to an isobaric actuation loading cycle. In such a thermomechanical cycle, the composite is loaded uniaxially and then subjected to a cooling and heating cycle under constant load so that the SMA undergoes both complete forward and reverse transformation.

RESULTS AND DISCUSSION

Using the above model, the effective response of the composite is determined. The strain-temperature response under a compressive loading of 100 MPa is presented in Fig. 2a along with the response of the dense SMA for comparison purposes. From the results in Fig. 2a, it can be seen that both the composite and the dense case exhibit a hysteretic response

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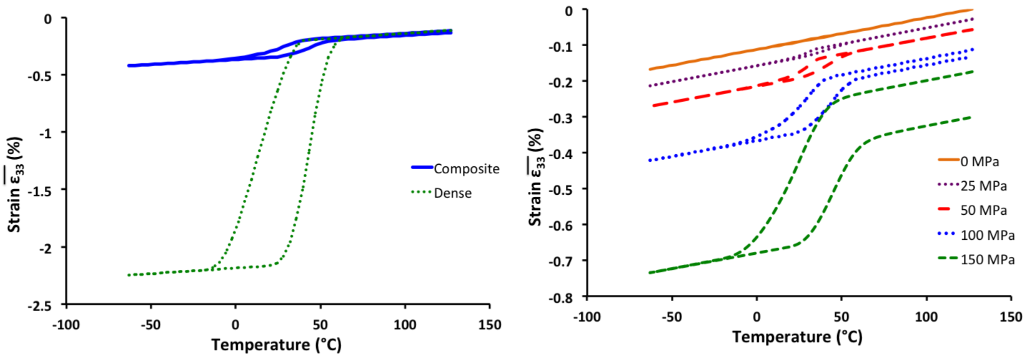
although the composite has a much reduced hysteresis and a corresponding decrease in the effective transformation strain. It is noted that such observations demonstrate the SMA phase undergoes transformation and those characteristics are still present in the hybrid composite. Interestingly, however, a shift in the effective transformation temperatures is observed.

To further consider this response, the composite is subjected to a variety of different applied loads and the associated



(a) Effective strain-temperature response of the hybrid composite and dense SMA under an applied compressive load of 100 MPa

(b) Effective strain-temperature response of the hybrid composite under compressive loadings of various magnitude

Figure 2. Effective strain-temperature response of hybrid SMA (a) through an actuation loading path under 100 MPa applied load along with the corresponding dense SMA response and (b) under a variety of different applied loads

strain-temperature responses are presented in Fig. 2b. From the results in Fig. 2b it is observed that when no mechanical load is applied and the composite is subjected to a thermal cycle, no hysteresis is observed. As the applied load increases, the resulting transformation strain and corresponding hysteresis size increase. Furthermore, it is important to note in Fig. 2b that as the applied loading increases the effective temperature corresponding to the completion of forward transformation *decreases*. This is in contrast to typical SMA behavior in which transformation temperatures increase with applied loading thus indicating an interesting interaction between the two materials present. As is clearly observed in the 150 MPa applied loading result, irrecoverable strains are generated through the transformation cycle leading to differences in initial and final strain levels and an open hysteresis loop. These strains are generated in the MAX phase and lead to the development of a residual stress state. Specifically, in the 150 MPa case, the MAX phase average stress in the direction of applied loading is 55 MPa at the completion of the thermomechanical cycle when the composite is unloaded. Due to this residual stress state, when the composite is then subjected to a thermal cycle without an applied load a hysteresis loop is observed. If, however, a tensile loading of 150 MPa is applied, a final stress of -50 MPa is generated corresponding to the desired compressive residual stress.

CONCLUSIONS

A micromechanical model was developed to determine the behavior of a hybrid SMA-MAX phase ceramic composite. Importantly, the model incorporated the effects of the microstructure by using realistic microstructures determined through x-ray tomography. Through numerical simulations, the response of the composite through an isobaric actuation loading cycle was explored. A reduction in the overall hysteresis size, shift in transformation temperatures and generation of irrecoverable strains were observed. Notably, the irrecoverable strains led to the development of a residual stress state in the composite and that specifically a compressive residual stress on the ceramic phase may be generated.

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