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Phase transition induced interfacial debonding in shape memory alloy fiber–matrix system

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ABSTRACT

This paper investigates the phase transition induced interfacial debonding of an embedded superelastic NiTi shape memory alloy (SMA) fiber in an epoxy matrix. In situ interfacial debonding morphology and the stress–strain responses of the fiber are obtained for different fiber diameter and surface roughness. It is shown that, depending on these fiber parameters, a ductile or a brittle debonding can occur. The ductile debonding is caused by the phase transition of the fiber and took place together with the propagating necking front of the martensite domain. Compared with the tension of a free-standing fiber, the fiber–matrix bonding can lead to an increase in the front propagating force (plateau) of the fiber. By using Griffith's energy balance approach, the crack surface energy is derived and the predictions of crack driving force agree well with the experimental data.

1. Introduction

Shape memory alloy (SMA) has shown great potential as a smart material capable of adapting its shape through large recoverable deformation. SMA in forms of wire, tube, strip or thin film (Feng and Sun, 2006; Zhang et al., 2010; Dong and Sun, 2012) has been used as large strain actuators to develop new functional composite materials (e.g. Xu et al., 2004; Zhang and Ni, 2007; Zafar and Andrawes, 2014) due to its extraordinary temperature-dependent shape memory effect (SME) and superelastic effect (SE). For SE, very large strain can be produced during the loading, but full recovery of the strain is achieved after a stress hysteresis upon unloading. SME refers to the phenomenon that SMA undergoes a large amount of residual strain and recovers its predetermined shape upon heating. Both phenomena are associated to a solid–solid phase transformation between austenite and martensite crystal phases, wherein the crystal structure changes from a high-symmetry cubic lattice B2 to a low-symmetry monoclinic lattice B19′ (Shaw and Kyriakides, 1995; Shaw and Kyriakides, 1997; Otsuka and Ren, 2005). These peculiar characteristics facilitate the direct integration of SMA fibers into a host matrix to form a composite to accomplish multi-functions such as sensing, actuation, self-adapting/healing of structures (Chen et al., 2006; Shajil et al., 2013; Kirkby et al., 2009). The composite reinforced by SMA fiber, as a new type of innovative adaptive/intelligent material, is gaining more and more practical applications in various fields, such as automotive components, retrofitting and strengthening of structural elements, shape control and biomedical devices (e.g. Morgan, 2004; Kuang and Ou, 2008; Muntasir-Billah and Alam, 2012). The SMA fibers were mainly used to tailor the overall performance of the composite in controlling its tension, bending or buckling (Johnalagadda et al., 1997; Janke et al., 2005; Song et al., 2006; Freed and Aboudi, 2008).

One of the key advantages to use SMA fiber in composites is to greatly reduce the possibility of catastrophic failure due to SMA's high yield strength and high recoverable strain from phase transition (PT) and crack bridging force during heating. The interfacial debonding associated with the PT of fiber and the formation of cracks along the fiber–matrix (F–M) interface can contribute significantly to the energy absorption capacity of the composite. In addition, the SMA fiber can help to bridge the macroscopic cracks, transfer the tensile stresses, resist the crack opening and dissipate the energy (Wang and Hu, 2005). In addition, the closure of cracks can also be achieved by simply heating the SMA fiber, as shown in Fig. 1.

Over the past few years, interfacial debonding failure between SMA fiber and matrix due to over-actuation of temperature or excessive deformation (e.g. Zhang and Ni, 2007; Kuo et al., 2009; Zhou and Lloyd, 2009; Raghavan et al., 2010; Fathollah et al., 2011; Lei et al., 2013) were observed in the experiments. Due to the importance of interfacial bonding in the integrity of composite, attempts have been made to investigate the stress transfer/distribution and the interfacial debonding phenomena

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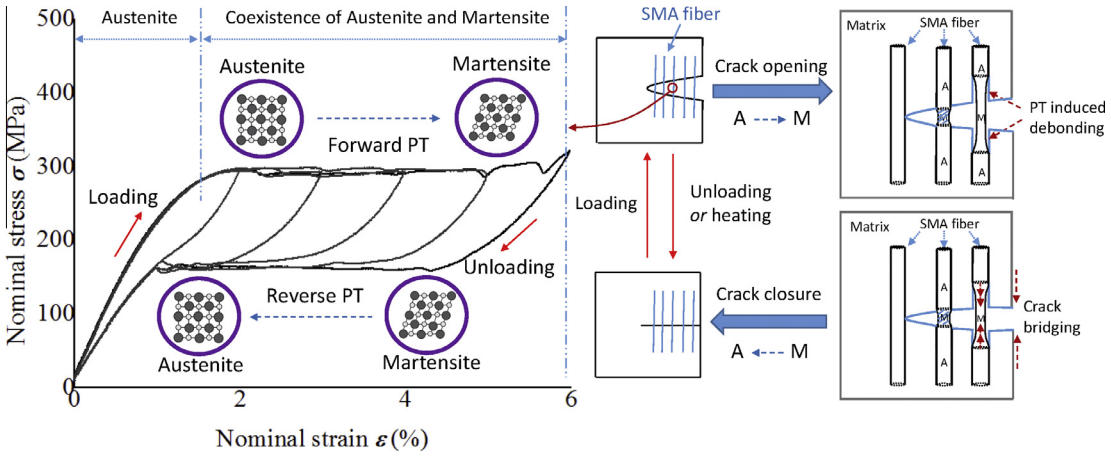

Fig. 1. The role of superelastic SMA fiber in the energy absorption and crack healing of composite during service.

(e.g. Lau et al., 2002; Wang and Hu, 2005; Payandeh et al., 2009; Poon et al., 2005). Improvement of the bonding between SMA fiber and polymer matrix were achieved by means of coatings or chemical treatment (e.g. Rossi et al., 2008; Neuking et al., 2008; Antico et al., 2012). However, systematic observations on the interfacial debonding process in SMA composite are still not available in the literature.

The objective of this paper is to perform an experimental investigation of the PT induced debonding process in a SMA composite under displacement controlled quasi-static tensile loading/unloading of the SMA fiber. In situ observations of interfacial debonding morphology were performed and the stress–strain hysteresis responses were captured. Different fiber diameter and surface roughness were used and the effects of these two parameters on the debonding response were examined. The materials and experimental set-ups are elaborated in Section 2. The experimental results of debonding morphology and stress–strain responses are presented in Section 3. In Section 4, we establish the interfacial debonding criterion and develop a theoretical model to evaluate the crack surface energy based on the energy balance approach. The conclusions are given in Section 5.

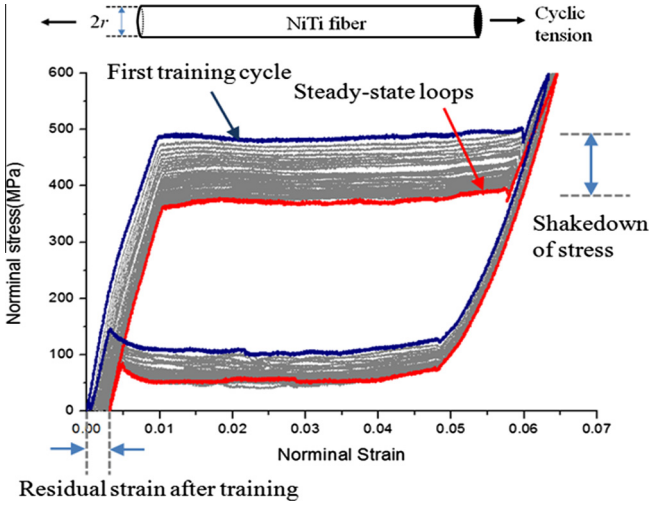

Fig. 2. Hysteresis loops of an as-received NiTi fiber under cyclic training.

2. Materials, sample preparation and experimental set-up

The SMA fibers used in the experiment are commercially available polycrystalline Nickel-titanium (NiTi) wire with oxide free surface (Johnson Matthey Inc., USA), which has a grain size of 100 nm. The fibers were cut from the same piece of NiTi wire to avoid significant deviations in material properties. The SMA has an austenite finish temperature (A_f) of 20 °C, which ensures a superelastic behavior during the experiment at a room temperature of 23 °C. Under such circumstance, the stress-induced martensite phase is expected during loading and the reverse transformation from martensite phase to austenite phase will occur during unloading. It has to be noted that, prior to the subsequent preparation of SMA composite specimens, the SMA fibers were fully trained through a number of cyclic tensile loadings. Fig. 2 depicts the general features of the hysteresis loops of an as-received NiTi fiber during training process. At the beginning, an initial homogeneous deformation of austenite phase is observed until the stress reaches a critical value of about 480 MPa with a maximum elastic strain around 1.2%. Thereafter, a macroscopic martensite domain starts to nucleate at each grip end, the stress remains at a plateau value until the fiber is fully transformed with the maximum strain of 6%. It is observed that there is a small stress drop preceding to the further elastic deformation of martensite phase, which is attributed to the annihilation of austenite as well as the merging of martensite domain. During unloading, an austenite band forms in the middle portion of the fiber and grows. The stretching and strain recovery of the NiTi fiber during loading and unloading are realized by the A–M interface motion, i.e., the growth/shrinkage of the nucleated martensite domain. After about 100 training cycles, the stress–strain curve eventually comes to a shakedown stage (stress stabilization) with repeating steady-state hysteresis loops. A gradual decrease and saturation of applied stress as well as a gradual increase and saturation of the residual strain can be observed (Yin et al., 2014). The purpose of this training process is to remove the effect of cyclic plasticity due to inherent material defect/dislocation, such that this cyclic effect in the subsequent debonding test can be ignored when evaluating the interfacial crack driving force. In addition, considering the stress/temperature sensibility in NiTi SMA is about 7 MPa/°C, the residual stress of about 21 MPa is a relative low value, the use of a larger difference between A_f and the test temperature is preferred in the future work to avoid the possible residual martensite.

The epoxy resin with a trademark of EpoxiCure™ (Buehler, USA) is used as the matrix, and it can be cured at ambient temperature. The epoxy and hardener were very carefully mixed to avoid air bubbles and slowly cast into an aluminum mould to produce a