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A monotonic loading approach for determining residual stresses of fiber reinforced metal matrix composites

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ABSTRACT

A monotonic loading approach called the monotonic loading-turning point approach (MLTPA) was proposed for the determination of residual stresses of fiber reinforced metal matrix composites. In MLTPA, monotonic tensile or compressive tests were carried out and the obtained stress–strain curves were used to determine the turning point stresses, according to which the matrix residual stresses were calculated using an analytical model developed in the present work. The approach was subsequently used to determine residual stresses of alumina fiber reinforced aluminum matrix composites and a good agreement was obtained between the residual stresses determined using the present approach and the cyclic loading approach.

1. Introduction

Continuous fiber reinforced metal matrix composites (CFMMCs) have received much attention owing to their excellent mechanical and physical properties in the fiber direction including high specific stiffness, high tensile and compressive properties and good fatigue resistance as well as high electrical conductivity [1–6]. It is well known that when a CFMMC is cooled down from the fabrication temperature to room temperature, residual stress is generated in the composite due to the great difference in thermal expansion coefficient between the metal matrix and alumina fibers [7]. It has been shown that residual stress may greatly influence the properties of metal matrix composites (MMCs) such as deformation, creep, dimensional instability, fracture strength as well as the fatigue resistance [8–12]. Hence much effort has been devoted to characterizing the residual stress that is existing in MMCs. The techniques used to characterize the residual stress in MMCs include X-ray diffraction, Neutron diffraction, Raman spectroscopy, tension/compression cyclic loading approach, nano-indentation, finite-element calculation, *etc.* Liu et al. [13] examined the distribution of thermal residual stress in SiC_f/Al composites using micro-X-ray diffraction (50 μm in diameter), and found that the hoop residual stress was tensile whereas the radial residual stress was compressive and the absolute value of the thermal residual stress decreased with the increase in the distance to the reinforcement/matrix interface. Ward et al. [14] determined the residual stress in two different SiC fiber-reinforced metal matrix composites using laser Raman spectroscopy, and found that the as-determined axial residual stresses coincided with those calculated using the continuous coaxial cylinder model. Bystrisky et al. [15] proposed a cyclic loading method to determine the matrix thermal residual stress in fiber-reinforced MMCs, in which tension–compression cyclic tests were performed and the residual stress was determined by using back-calculated *in-situ* matrix stress–strain curves. This method has been verified to be valid for fiber-reinforced MMCs. Olivas et al. [16] measured surface residual stresses in SiC particle-reinforced Al matrix composites with a nano-indentation technique, and found that the measured residual stress in the Al matrix was in reasonable agreement with the numerical modeling results. Finite-element method (FEM) [17–20] is often used to characterize the detailed residual stress distribution around reinforcements in MMCs and determine the influence of materials and structural parameters on residual stress by performing parametric analysis. Besides, theoretical models for evaluating matrix residual stress of particle-reinforced composites have been developed including concentric sphere model, Eshelby model, *etc.* [21]. For continuous-fiber-reinforced composites, Zhang and Anderson [22] developed a simplified axisymmetric model and predicted well the thermal residual stress in continuous fiber-reinforced composites.

In the present work, a monotonic loading approach, in which only monotonic tension or compression tests were carried out, was developed to determine the residual stress existing in fiber-reinforced MMCs. The approach was subsequently used to determine the residual stress of alumina fiber reinforced aluminum

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matrix composites and a good agreement was obtained between the residual stresses determined using both the present approach and the cyclic loading approach proposed by Bystrisky et al. [15].

2. Methodology

The approach developed in the present work to determine residual stresses of fiber reinforced MMCs is a kind of monotonic loading approach called the monotonic loading-turning point approach (MLTPA). In the approach, only a monotonic tension or compression test is needed to determine the residual stress of a fiber reinforced metal matrix composite.

During a monotonic loading (tension or compression) along the fiber direction, Young's modulus of a continuous fiber reinforced MMC, E_c, can be expressed using the rule of mixture as

$$E_c = V_f E_f + V_m E_m \quad (1)$$

where E_f and E_m are Young's moduli of the fiber and the matrix, respectively; V_f and V_m are the volume fractions of the fiber and the matrix, respectively. When the matrix yields, its tangent modulus will decrease significantly from its elastic modulus E_m (elastic deformation stage) to its tangent modulus E_{mp} (plastic deformation stage), leading to a considerable decrease in E_c and hence a turning point (yielding point) on the tension or compression stress–strain curve of the composite. According to the rule of mixture, the turning stress, *i.e.* yielding stress of the composite,σ_{yc}, can be expressed as

$$\sigma_{yc} = V_m \sigma_{ym} + V_f \sigma_f \quad (2)$$

where σ_{ym} is the *in-situ* yielding stress of the matrix, σ_f the stress borne by the fiber.

For a fiber composite with a tensile matrix residual stress, when a compression test is carried out, there should be a yielding point (*i.e.*, turning point on the compression stress–strain curve) because of the compressive yielding of matrix. Schematic drawings of the stress–strain relationship during compressive loading are shown in Fig. 1.

According to Eq. (2), the *in-situ* matrix compressive yield stress, σ_{ym}, can be expressed as

$$\sigma_{ym} = \frac{\sigma_{yc} - V_f \ \sigma_f}{V_m} = \frac{\sigma_{yc} - V_f \ E_f \ \varepsilon_{yc}}{1 - V_f} \quad (3)$$

where ε_{yc} is the yield strain, *i.e.*, the turning point strain (see Fig. 1a).

For an elastic matrix tensile residual stress, it can be seen from Fig. 1b that during the compressive loading of a fiber-reinforced composite, the matrix undergoes a compressive deformation including an elastic recovery (from point A to point O) and elastic compressive deformation (from points O to point B) and plastic compressive deformation (from point B to point C). Assuming the compressive yield stress of the matrix is equal to its tensile yield stress σ_{ym0} (here the Bauschinger effect is ignored for simplicity), the *in-situ* matrix yielding stress, $\sigma_{ym,}$ should have the magnitude as shown in Fig. 1b. Then the relationship between *in-situ* matrix yielding stress and the matrix residual stress is

$$\sigma_{res} = \sigma_{ym} - \sigma_{ym0} \quad (4)$$

Combining Eqs. (3) and (4), the matrix residual stress can be expressed as follows:

$$\sigma_{res} = \frac{\sigma_{yc} - V_f \ \sigma_f}{V_m} - \sigma_{ym0} = \frac{\sigma_{yc} - V_f E_f \varepsilon_{yc}}{1 - V_f} - \sigma_{ym0} \quad (5)$$

Similarly, for a fiber-reinforced composite with a plastic tensile residual stress, the stress–strain relationship of the matrix during the compressive loading of the composite should have the form as shown in Fig. 1c and the matrix residual stress can be also expressed by using Eq. (5).

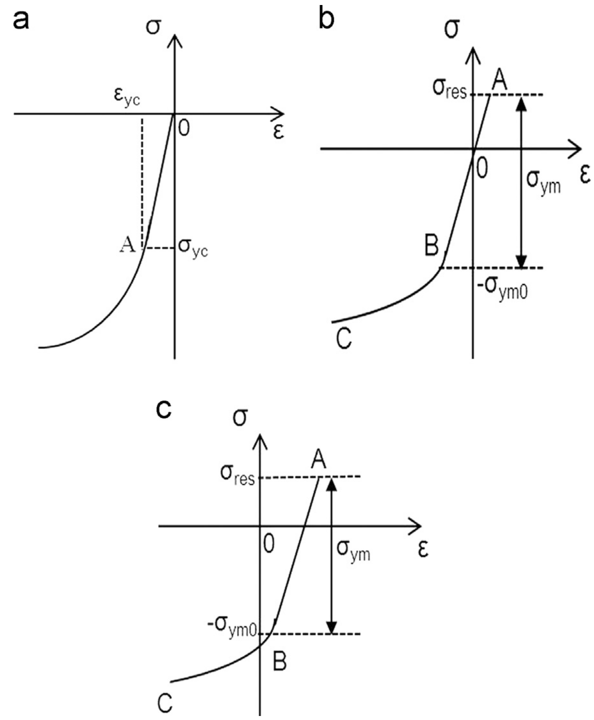

Fig. 1. Schematic drawings of stress–strain relationship during compressive loading of a fiber-reinforced composite: (a) compressive stress–strain relationship of the fiber-reinforced composite; (b) matrix stress–strain relationship during compressive loading with elastic matrix residual stress; and (c)matrix stress–strain relationship with plastic residual stress.

Therefore, for a fiber-reinforced composite with a tensile residual stress, the matrix residual stress can be obtained by performing a compression test and solving Eq. (5).

For a fiber-reinforced composite with a compressive matrix residual stress, when a tension test is carried out, there should be a yielding point (*i.e.*, turning point on the tension stress–strain curve) because of the tensile yielding of matrix. Schematic drawings of the stress–strain relationship during tension loading are shown in Fig. 2.

According to Eq. (2), the *in-situ* tensile yield stress in the matrix, σ_{ym}, can be also obtained using Eq. (3).

It can be seen from Fig. 2b that during the tensile loading of the fiber-reinforced composite with an elastic compressive residual stress, the matrix undergoes compressive deformation including an elastic recovery (from point A to point O) and elastic compressive deformation (from point O to point B) and plastic compressive deformation (from point B to point C). The *in-situ* matrix yielding stress, $\sigma_{ym,}$ should have the magnitude as shown in Fig. 2b and the relationship between the *in-situ* matrix yielding stress and the elastic matrix residual stress can also be expressed using Eq. (5).

Similarly, for a fiber-reinforced composite with a plastic compressive residual stress, the *in-situ* stress–strain relationship of the matrix during the tensile loading of the composite should have the form as shown in Fig. 2c and the matrix residual stress can also be expressed by using Eq. (5).

Therefore, for a fiber-reinforced composite with a compressive residual stress, the matrix residual stress can be obtained by performing a tensile test and solving using Eq. (5).

3. Experimental verification

3.1. Materials

To verify the validity of the present approach, a 45 vol% continuous Nextel™-610 alumina fiber reinforced pure aluminum