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Uniaxial mechanical properties of multi-layer thin films in use for scientific balloons

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Abstract

Essential and accurate mechanical parameters of multi-layer thin films for scientific balloons are indispensable for performing structural analysis. This study focuses on the determination of uniaxial mechanical properties of a new multi-layer thin film and the understanding of the effects of mechanical properties on structural behavior and altitude with three-dimensional numerical models. For uniaxial monotonic mechanical properties, a method to determine yield stress is proposed in combination of geometrical and energetic principles. It is found that average yield stresses are 20.5 MPa and 15.0 MPa for machine and transverse directions. The cyclic mechanical properties in terms of elastic modulus and ratcheting strain tend to be stable after certain cycles. Moreover, the Poisson's ratios of 0.31 and 0.15 in machine and transverse directions are determined with digital image correlation (DIC) technique. Furthermore, these mechanical properties are utilized to analyze a 12 m diameter spherical superpressure balloons floating at the altitude of 20 km. A corresponding three-dimensional numerical model is developed to understand the effects of mechanical properties on structural behavior and altitude. The numerical results in terms of elastic moduli show that the effects of mechanical properties on structural behavior and altitude are relatively apparent and slight, respectively.

Keywords: Elastic modulus; Mechanical properties; Multi-layer thin film; Scientific balloon; Ratcheting strain; Yield stress

1. Introduction

Scientific balloons with effective payload at a high altitude, such as VEGA balloons (Kremnev et al., 1986), environmental balloons (Saito et al., 2006) and ultra long duration balloons (Cathey, 2007), can be used for upper atmospheric research and meteorological observations (Smith, 2004, Gregory, 2006). The zero-pressure balloons with openings at the bottom to prevent over-pressure are typically used for conventional scientific missions (Smith, 2004). The altitude variation during working period due to day night cycling can influence observation results. To keep a stable altitude, super-pressure balloons that maintain a positive internal pressure in relationship to the external environment are proposed to fly at a specific altitude with a known payload (Jones, 2014, Said, 2002).

Generally, uniaxial mechanical properties, including elastic modulus, yields stress, ultimate strength and breaking elongation are essential parameters for designing zero-pressure and super-pressure balloons. The super-pressure balloons experience over-pressure and thermal effects since varying environmental temperature causes unbalanced states according to ideal gas equations. The variations of

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internal and external parameters affect structural behavior and corresponding observation results, especially for thin-film balloons. The pressure variation in response to environmental effects requires cyclic mechanical properties to understand detailed structural behavior (Hu et al., 2014). Moreover, biaxially tensioned balloons can be calculated with the combination of uniaxial mechanical properties and Poisson's ratio. Based on these requirements and from the perspective of analysis and design, uniaxial tensile mechanical properties are indispensable for understanding material mechanics and structural behavior, such as yield stress from uniaxial monotonic tensile tests (Hu et al., 2015), ratcheting strain and Poisson's ratio from uniaxial cyclic tests (Hu et al., 2014). In general, these mechanical properties are dependent on specific material components (polymers or composites).

For polymer materials, Kumar et al. (2008) focused on tensile mechanical properties of a polyethylene material, named as 'ANTRIX' film, and compared with Stratofilm 372 and Astro-D film to validate the feasibility of using this film for scientific balloons (Kumar et al., 2008). Strganac et al. (1991) investigated the effects of low earth orbit environments on basic properties of balloon materials, finding that chemical changes observed from the SEM micrographs (crystallinity decreased but branching and crosslink frequency increased) occurred due to thermal cycling (Strganac et al., 1991). Saito et al. (2002, 2006) developed the 3.4 μm and 2.8 μm films for 5000 m^3 balloons which successfully achieved the 43 km and 42.6 km altitudes (Saito et al., 2002, 2006). Gerngross et al. (2008) found that creep properties of polymer materials can affect prediction accuracy and cause stress redistribution (Gerngross et al., 2008). A further investigation concluded that the change in geometry over time needed to be checked to satisfy functional requirements over the service life (Said, 2004). However, technical limitations exist for thin films used for ultra long duration balloons and these polymer materials are hard to meet all requirements of strength, mass, gas retention, sulfuric acid resistance and radiative heat transfer. In this case, laminate materials would be necessary for specific scientific balloons, such as Venus balloons (Kremnev et al., 1986) and certain ultra long duration balloons (Said, 1999a, 1999b).

For multi-layer laminates for a Venus balloon, it is reported that tensile strengths of warp and fill specimens were 71 kN/m and 57 kN/m (Hall et al., 2008). Said (1999a, 1999b) concentrated on fabric-film laminates composed of woven polyester fabric, homogeneous polyester film and a linear low density polyethylene. The quantitative assessment indicated that the incremental percentages of breaking strength and stiffness were 26% and 18% from 0.07 mm/min to 762 mm/min (Said, 1999a, 1999b). Li et al. (2015) evaluated uniaxial mechanical properties of co-extruded three-layer linear low density polyethylene in order to develop a large-strain thermo-viscoelastic model (Li et al., 2015). Sterling (2003) carried out a series of experiments on a poly (para-phenylene-2, 6-benzobisoxzole) fiber and showed that measured strength was smaller than direct scale-up fiber-strength because of braiding process and material ageing (Sterling, 2003). In addition, typical materials used for stratospheric structures (thick and heavy) are not suitable for balloons at a desired altitude. Therefore, developing new materials that are lightweight and strong enough is necessary to achieve specific scientific aims. Considering weight, strength, environmental effects and current techniques, the multi-layer thin film can meet these requirements.

On the whole, uniaxial monotonic mechanical properties are indispensable for preliminary design and analysis of scientific balloons. However, accurate mechanical properties can be helpful for analyzing structural behavior resulting from day night cycling. The thermal effects and inner pressure fluctuate during launching and working period, causing stress/strain changes. The stress and strain are related to structural safety and deformation/volume (Schur, 2002). Therefore, cyclic mechanical properties are necessary for analyzing structural behavior to ensure safety performance of balloon structures. Using cyclic mechanical properties for analysis of structural behavior has been revealed with several aerospace structures, such as inflated stratospheric platforms (Hu et al., 2017b) and inflated membrane structures (Glaser, 2016). For these reasons, uniaxial monotonic and cyclic mechanical properties are both critical for assessing new materials for aerospace structures.

For a scientific balloon project (a 12 m diameter spherical superpressure balloons floating at the altitude of 20 km), a new multi-layer thin film is developed based on the requirements of space environments and scientific missions. The uniaxial mechanical properties and structural behavior are essential but unavailable due to its newness. Thus, this paper focuses on the determination of uniaxial mechanical properties of the multi-layer thin film and the understanding of the effects of mechanical properties on structural behavior and altitude with three-dimensional numerical models.

The composition of this paper is organized as follows. Uniaxial monotonic and cyclic experiments with specific considerations are detailed in Section 2. Mechanical parameters, such as yield stress, ratcheting strain and Poisson's ratio, are determined from experimental results with suitable methods in Section 3. A numerical analysis with a three-dimensional model of the scientific balloon is performed to understand the effects of mechanical properties on structural behavior and altitude in Section 4. Finally, useful observations and values are summarized in the Conclusions.

2. Experimentation

2.1. Materials and specimens

The material used in this study is a multi-layer thin film made of the following layers bonded together from outside