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The heat build-up of a polymer matrix composite under cyclic loading: Experimental assessment and numerical simulation

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ABSTRACT

In order to experimentally measure the heat build-up within a polymer matrix composite under cyclic loading, the real-time temperature monitoring of a solid composite propellant (HTPB propellant) subjected to cyclic uniaxial, strain-controlled fatigue tests at various loading conditions was carried out. The results obtained show that surface temperature of HTPB propellant during the fatigue test increased by up to dozens of degrees, which due to its viscoelastic nature. The effect of applied strain levels and frequencies of tested material on the deterioration of HTPB propellants during fatigue process were quantitatively assessed by the variation of dynamic moduli. It has confirmed that the influences of self-heating on tested materials mainly lies in softening polymeric matrix and extended debonding along particle/matrix interface. Additionally, the pattern of increased fatigue lifetime with a reduction in loading frequency and strain level under was also observed. Moreover, based on an uncoupled thermomechanical coupling algorithm, the finite element analysis incorporating a hyper-viscoelastic constitutive model of tested material was proposed to simulate the mechanical and thermal responses of tested material. The results of simulation agree well with experimental ones, which helps to validate the accuracy of proposed model.

1. Introduction

Over the past decades, polymer matrix composites (PMCs) are increasingly being utilized as the energetic resource of solid rocket motors. For instance, the solid composite propellant (SCP), with polymeric binder serving as its matrix, has received considerable attention due to its high specific impulse and excellent mechanical properties, thus it is widely used in military and aeronautics fields that are expected to suffer complex and harsh loading conditions [1].

Throughout the lifespan of solid rocket motors, they are subjected to a variety of dynamic loadings, especially cyclic loading in the process of transportation or being mounted under the aircrafts. While subjected to aforementioned mechanical loading, energy dissipated (also known as intrinsic mechanical dissipative work) due to the viscoelastic nature of the binder of SCP [2] in turn caused so-called heat build-up (or self-heating) effect, which is irreversible and cannot be neglected for the following reason. In one vital point, since the fact that heat generation occurs within the material and the heat energy is not easily conducted away in virtue of the material's unique weak thermal properties, heat generation causes an increase in temperature inside the material, which can even lead to melting of the material or explosive rupture. However, in most available publications on solid propellants, self-heating of the tested sample was seldom analysed; instead, an average temperature, always the ambient temperature, was deliberately adopted as the sample temperature, which fails to represent the change of temperature field and its impact on the material.

There are some similarities in terms of the chemical structures and physical properties between SCP and rubber, fortunately, researches concerning heat build-up of the latter were quite a few. According to a number of literatures [3], heat build-up heavily restricts the development of high performance tires (the materials of modern pneumatic tires are synthetic rubber and natural rubber, along with carbon black and other chemical compounds) because the rising temperature deteriorates the mechanical responses of rubber compounds greatly; for instance, high temperature can lead to material aging, or fatigue life shortening. Likewise, self-heating alters the mechanical properties of the rubber-like materials through temperature increments. Solid propellants can be assigned to the group of viscoelastic polymeric composites with their mechanical properties being similar to that of general rubber-like polymers.

Essentially, the heat build-up is a consequence of an energetic dissipation illustrated by the hysteresis loop observed on the strain-stress

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response under cyclic loading. The prediction of heat build-up, which helps to quantitatively assess its impact on SCP, requires the resolution of both mechanical and thermal equations. To the best of our knowledge, three main resolution methods found in the literature to numerically solve this problem [4] are as follows: (1) Fully coupled algorithm [5]: the mechanical and thermal problems are solved at the same time; (2) Fractional step algorithm: the thermomechanical problem is split into two simpler problems that are solved separately (at each time increment, the mechanical problem is solved first and then the thermal problem is solved); (3) Uncoupled algorithm [6]: deformation, dissipation and thermal modules are included in this part; firstly, the mechanical problem is solved for one cycle, then the dissipation is estimated and the thermal problem is solved for many cycles on one fixed geometry until the rise of temperature is significant, thus the mechanical problem is updated using the actual temperature.

Due to its low computational cost, uncoupled method is really appealing to those attempts to solve the thermomechanical coupling problem that occurs under cyclic loading. For modeling the phenomena of the self-heating during fatigue process, the finite element method (FEM) could be used as well [7]. The FEM is one of the numerical methods for solving differential equations that describe many engineering problems. The FEM, originated in the area of structural mechanics, has been extended to other areas of solid mechanics and later to other fields such as heat transfer and fluid dynamics [8]. In present study, FEM method is adopted to solve the thermomechanical coupling problem with respect to fatigue-induced heating [9]. The simulation of the mechanical and thermal responses of cyclically loaded SCP would be accomplished with the application of FEM in this study.

The main objective of this paper is to assess the heat build-up (self-heating effect) of a typical SCP subjected to strain-controlled cyclic loading with various loading amplitudes and frequencies. The definition of material properties was based on experimentally determined dynamic moduli of the material. Furthermore, the finite element analysis incorporating a developed hyper-viscoelastic constitutive model was carried out to simulate the mechanical and thermal responses of tested material. The results had shown that the numerical simulations agreed well with experimental ones, which validated the accuracy of proposed model. It is believed that the research will promote the interpretation of thermomechanical coupling in the course of fatigue for SCP and lay a groundwork of constitutive modelling including the dependence of temperature on material properties.

2. Theoretical foundation

2.1. Heat build-up of SCP

2.1.1. Viscoelasticity

The heat build-up in rubber-like material is the feature of the nonlinear viscoelasticity due to internal frictions between polymer chains-polymer chains, polymer chains-particles, and particles-particles [10]. During the cyclic loading, internal frictional dissipation mechanisms convert most of the supplied mechanical strain energy into heat. The self-heating excited by cyclic mechanical loading is directly correlated to the stress level and the cyclic frequency. If applied strain is given as:

$$\varepsilon^* = \varepsilon_0 e^{i\omega t} \tag{1}$$

where ε_0 represents the strain amplitude, $\omega(=2\pi f)$ represents the angular angle, and t represents the time. As a result of viscos effect, the strain is lagging behind the stress, therefore the corresponding stress comes:

$$\sigma^* = \sigma_0 e^{i(\omega t+\delta)} \tag{2}$$

where σ_0 is the stress amplitude and δ is the phase angle between stress and strain. The complex modulus, E^*, is defined as the ratio of stress to strain [11]:

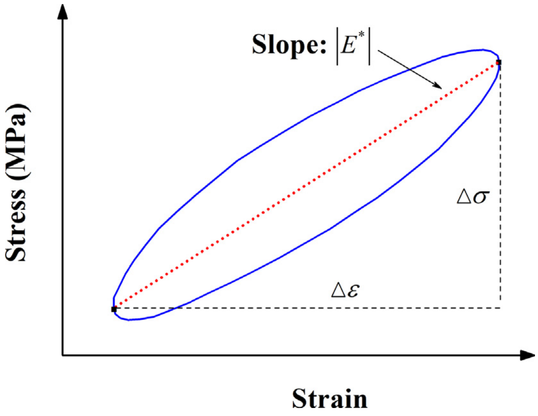

Fig. 1. Definition of dynamic modulus in a hysteresis loop.

$$E^* = \frac{\sigma^*}{\varepsilon^*} = \frac{\sigma_0}{\varepsilon_0}(\cos\delta + i\sin\delta) = E' + iE'' \tag{3}$$

where the storage modulus is defined as $E' = \sigma_0/\varepsilon_0\cos\delta$ and the loss modulus is defined as $E'' = \sigma_0/\varepsilon_0\sin\delta$. In present study, $|E^*| = \sigma_0/\varepsilon_0$ is acquired by obtaining the slope of stress versus strain, $\triangle\sigma/\triangle\varepsilon$, in a hysteresis loop, as depicted in Fig. 1. In other words, $|E^*|$ is regarded as dynamic modulus during cyclic loading [12].

The hysteresis energy density per cycle D_0 is calculated as following:

$$D_0 = \oint \sigma d\varepsilon = \pi\sigma_0\varepsilon_0\sin\delta = \pi\ |E^*|\ \varepsilon_0^2\sin\delta \tag{4}$$

Thus the mechanical energy release rate, $\dot{D}$, was obtained by multiplying loading frequency, f:

$$\dot{D} = f\cdot D_0 = f\pi\ |E^*|\ \varepsilon_0^2\sin\delta \tag{5}$$

It has to be noted that the dissipated energy is not totally converted to heat [13], while part of that is responsible for microstructure adjustments or microcrack initiation, etc. within the material. For instance, Rittel [14,15] investigated the self-heating of two kinds of commercial polymers, PC and PMMA, with experimental and theoretical approaches. The authors argued that apart from the fraction of mechanical energy ($\dot{D}$) converted to heat, the rest of the loss energy (1-$\dot{D}$) was responsible for structural modifications in the material.

2.1.2. Microplasticity

The damage is defined as the deterioration of the mechanical properties of materials or structures due to the initiation and propagation of micro structural defects such as microcracks or microvoids under the external loads or environments. There are a variety of materials or components damage, such as brittle damage, plastic damage, creep damage, and fatigue damage, etc. In this case, progressive damage of SCP during fatigue tests included particle cracking, debonding along particle/binder interfaces, and void nucleation inside the material [16]. Therefore, another possible contributing factor for heat generation of SCP are possible flaws, defects within SCP due to the preparation or transportation process. Once subjected to exterior mechanical loading, these points or areas are often plastically deformed even if the bulk specimen undergoes viscoelastic deformation. Given the fact that the viscoelasticity was assumed to be the main dissipative source, the microplastic deformation induced heat generation [17] was ignored due to its minimal influence in this study.

2.1.3. Temperature evolution

The fatigue of polymeric composites is a sophisticated thermo-mechanical coupling process accompanying the mechanical energy release and heat dissipation [18,19]. The typical profile of surface temperature evolution of SCP [20] was illustrated in Fig. 2, which includes an initial transient stage (adiabatic state) and the following isothermal stage (at that time the surface temperature of specimen remains

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