Materials & Design 128 (2017) 47–55

Contents lists available at ScienceDirect

Materials & Design

journal homepage: www.elsevier.com/locate/matdes

Excitation of thermal dissipation of solid propellants during the fatigue process

Xin Tong[a], Xiong Chen[a], Jinsheng Xu[a,*], Chaoxiang Sun[b], Wei Liang[a]

[a] School of Mechanical Engineering, Nanjing University of Science & Technology, 210094 Nanjing, China
[b] Beijing Institute of Space Long March Vehicle, China Aerospace Science and Technology Corporation, 100076 Beijing, China

ARTICLE INFO

Keywords:
Fatigue
Heat dissipation
Infrared thermography
Solid propellants
Stored energy

ABSTRACT

By using the infrared thermographic method, a non-destructive testing technique was applied to detect the surface-temperature evolution of solid propellants during strain-control fatigue tests within finite cycles. When the applied strains were below the viscoelastic limit, two stages of temperature variation were observed before the initiation of macroscopic cracks: an initial temperature-increase stage, and a steady temperature state. Thermodynamic analysis was carried out and a method was developed to allow the acquisition of stored energy at different stages of cyclic loading, which can reflect the material damage on the macroscopic scale. In addition, temperature localization during fatigue was observed, which implied the occurrence of damage accumulation and crack propagation. The results reveal that the cyclic-loading induced temperature increase of solid propellants during the fatigue process has a significant effect on solid rocket motors in a transportation or storage state.

1. Introduction

Solid rocket motors (SRMs) have been extensively applied in the military and aerospace fields. Solid propellants serve as energy sources of SRMs and are composite materials with a complex microstructure. In general, solid propellants consist of a polymeric binder (e.g., hydroxyl-terminated polybutadiene, HTPB), crystal oxidizer (e.g., ammonium perchlorate), and fuel particles (e.g., aluminum). Because of the viscoelastic nature of solid propellants, their mechanical properties are sensitive to temperature and the rate of deformation. Severe stressing and extreme temperatures induce damage which is manifested in particle cracking, dewetting along particle/polymer interfaces, void nucleation, and growth [1]. Nevertheless, during the fatigue process of the material, deformation-induced heat dissipation increases the internal temperature and is harmful to SRMs. Thus, the temperature field inside the propellant is no longer consistent with its surroundings during the fatigue process, which makes it more challenging to predict the degradation process of propellants during transportation or storage. It is well known that aging is a natural and irreversible process that polymers undergo, and one of the influencing factors is temperature. An elevated internal temperature would speed up the movement of polymer chains, and once the chemical bond dissociation energy is exceeded, thermal degradation of polymer chain is induced, resulting in accelerated aging. The deformation-induced temperature variation will affect the various changes leading to degradation of mechanical properties, including the effect of temperature on the binder-particle surface energy and on chemical mechanisms such as bond scission [2]. Interfacial mechanical characteristics of SRMs are also influenced by the fatigue-induced calorific effect. The maximum load, fracture energy, and adhesive strength between the insulated layer [as in ethylene propylene diene monomer (M-class) (EPDM) rubber] and adhesive decreased with elevated temperature [3]. Owing to the internal friction during the fatigue process, thermal dissipation is incited and causes a subsequent considerable temperature increase. Propellant is bonded cohesively with the coating layer and shell of the combustion chamber inside the SRMs. Once the temperature field of the propellant is elevated due to the excitation of external shock, heat flux will flow to the propellant-coating layer interface and then soften the local area, which may give rise to de-bonding phenomena. Therefore, with respect to the fatigue deformation of propellant, special attention should be paid to investigation of the self-heating effect.

Previous researchers have focused mainly on the ambient-temperature change during the deformation process, while omitting the temperature variation of the tested material. Neglecting temperature variations induced by the deformation eliminates the possibility of establishing complete energy balances. The priority of thermomechanical coupling is to detect a temperature increase by effective methods; for instance, infrared thermography and the use of thermocouples [4].

* Corresponding author.
E-mail addresses: tongxin@njust.edu.cn (X. Tong), xujinsheng@njust.edu.cn (J. Xu).

http://dx.doi.org/10.1016/j.matdes.2017.04.088
Received 16 December 2016; Received in revised form 24 April 2017; Accepted 25 April 2017
Available online 28 April 2017

Temperature measurements using thermocouples suffer from the disadvantage that temperature data are collected from one or more discrete locations; another limitation is the possible heat conduction by the thermocouple, which may interfere with the thermal data readings [5]. On the other hand, high-performance infrared cameras are widely used to effectively and simply record the temperature variation accompanying fatigue deformation, and their use forms the basis of quantitative infrared thermography [6]. Temperature-measurement techniques have been used to predict the location of fatigue damage, to monitor fatigue crack propagation, and to determine fatigue limits. A research group led by Zhang conducted a series of experiments and carried out a theoretical analysis of the fatigue lifetime of AZ31B magnesium alloy and of the fatigue behavior of its welded joint using infrared thermography [7,8]. Liakat et al. developed a non-destructive testing method to predict the remaining fatigue life of metallic specimens using the prior history of fatigue damage [9]. Amiri et al. [10] showed that the slope of the temperature curve at the beginning of the test could be utilized as an index for fatigue-life prediction. Jiang et al. [11] introduced a model incorporating internal state variables to predict the mechanical and thermal response of ULTIMET® alloy subjected to low-cycle fatigue; they also deemed that the temperature during fatigue tests reveal the accumulation of fatigue damage. Yang et al. [12] conducted in-situ observations of the mechanical damage behavior of bulk metallic glasses (BMGs) during both fatigue and tensile testing provided by thermography, and quantified the relationship between temperature evolution and stress-strain behaviors during high-cycle fatigue. A large-strain thermo-viscoelastic constitutive model to describe the self-heating of rubber materials during low-cycle fatigue response was developed by Rodas et al. [13]. The methods assume that the recorded temperature variation caused by cyclic loading of a test specimen is a measure of the heat dissipation due to intrinsic energy dissipative mechanisms. However, corresponding research concerning solid propellants have yet to be analyzed.

In the present study, an infrared thermographic method was introduced to research the calorific process of HTPB propellant during finite-cycle fatigue tests. The aim of this paper is to analyze thermo-mechanical coupling during the fatigue process of HTPB propellant by capturing the temperature evolution of HTPB specimens. The fraction of mechanical energy dissipation was also determined on the basis of complete energy-balance equations to quantitively obtain the amount of stored energy.

2. Experiment

2.1. Materials and specimens

The HTPB propellant investigated is a particle-filled composite composed of 17-wt% Al (aluminum), 70-wt% AP (ammonium perchlorate), and 13-wt% of a HTPB (hydroxyl-terminated polybutadiene) matrix and other additives. Fig. 1 is a scanning-electron-microscopy (SEM) image of HTPB propellant. From the image, information about distribution can be determined; that is, the large particles are AP and the main portion is the HTPB matrix, with *Al* and other additives distributed randomly inside the matrix.

The thermophysical parameters of HTPB propellant [14,15] are listed in Table.1. The heat-transfer coefficient h is evaluated using the following empirical expression for a vertical flat plate [16]:

$$h = 1.42\left(\frac{T_s - T_\infty}{L}\right)^{0.25} \quad (1)$$

where T_s and T_∞ represent the surface and the ambient temperature, respectively, and L represents the specimen length between the grips. These parameters were temperature dependent, but could be identified as constant since the temperature change was considerably small and could be neglected.

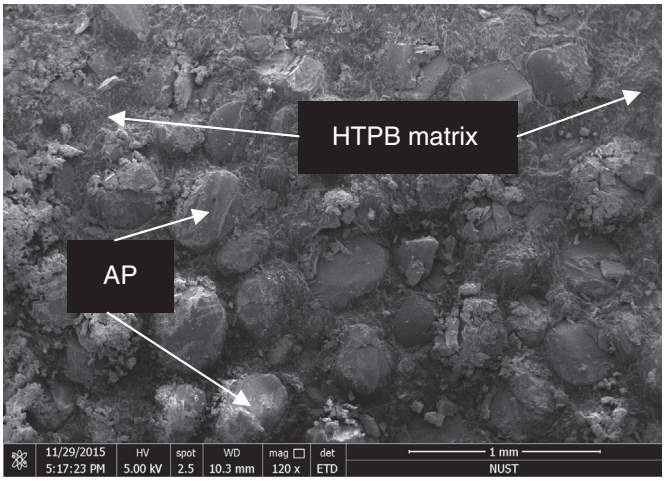

Fig. 1. SEM image of HTPB propellant.

Table 1
Thermophysical parameters of HTPB propellant.

Parameter	Value
Density, ρ[kg/m^3]	1770
Specific heat, c[J/(kg·K)]	1500
Coefficient of heat conduction, λ[W/(m·K)]	0.3

In the preliminary experiment conducted, it was found that HTPB propellant was difficult to fix firmly in the grips of the test equipment. In order to avoid unexpected experimental inconvenience, such as unstable loading conditions or inaccurate gauge length, a self-designed collet (made of 45# steel) was used, and the collet was adhesively fixed to the tested specimen using AB adhesives (especially useful for polymers and metals). The specimens were prepared according to the configuration shown in Fig. 2. Prior to each test, the specimens were stored inside the temperature chamber for 24 h to eliminate potential moisture from the surrounding environment.

2.2. Equipment and test procedure

The mechanical and thermal response of tested specimens were recorded using two methods. The uniaxial tension-compression fatigue tests were performed on a dynamic mechanical analyzer (Model No. DMA-ELF3200, BOSE® Corp., USA), which possesses excellent abilities to control the applied loading range (from -225 to 225 N), frequency (from 5×10^{-5} to 200 Hz) and temperature (with temperature control device, from -150 to 315 °C) and is qualified to accomplish tensile, compressive, and fatigue tests. The force and displacement data were recorded by sensors with high accuracy, whose resolutions were 0.01 N and 0.001 mm, respectively.

An infrared thermal camera (Model No. FLIR A615, FLIR® Systems, Inc., USA) was employed to capture the distribution of heat sources on the surface of the HTPB propellant specimens after processing thermal information with its supporting software. The IR camera had a 640 × 480-pixels, focal-plane-array uncooled microbolometer, which was sensitive to 7.5–14 μm wavelength thermal radiation. The temperature resolution of the camera was 0.05 °C at 30 °C with a thermographic map acquisition rate of 25 Hz. During the fatigue test, the IR camera was positioned on a tripod with its focal plane perpendicular to the lateral surface of the HTPB specimen. Before fatigue testing, a thin graphite coating (black matte paint) was applied to the specimen surface in order to reduce IR reflections and to increase the thermal emissivity of the specimen surface (in this case, the emissivity was