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Strain rate and temperature dependence of the compressive behavior of a composite modified double-base propellant

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ABSTRACT

The quasi-static and dynamic compressive properties of a composite modified double-base (CMDB) propellant were studied over a wide range of strain rates from 10^{-4} s^{-1} to 10^3 s^{-1} at low temperatures of −40 °C to 0 °C, using a conventional universal testing machine and a split Hopkinson pressure bar apparatus. The experimental results show that the mechanical properties of the CMDB propellant, in terms of yield stress, initial compressive modulus, and ultimate strain, were greatly affected by the applied strain rate and the temperature, and the stress–strain responses exhibited an initial viscoelastic phase, followed by yielding, and then a subsequent strain hardening or softening stage, which was strongly dependent on the strain rate and temperature. It was found that the yield stress increased with both increasing strain rate and decreasing temperature. According to the experimental results, the strain rate effect, but not the temperature effect, was accentuated at higher rates. Moreover, the Eyring cooperative model was employed to predict the yielding behavior, and a master curve of reduced yield stress versus strain rate was built. The results show that the Eyring cooperative model provides reasonable prediction over a wide range of strain rates under low temperatures.

1. Introduction

Propellant grains serve as the energy source of solid rocket motors (SRMs), in which the fuel and oxidizer are both incorporated, and their mechanical properties are as important as their ballistic properties to guarantee proper motor functionality (O'Neil and Heister, 2014). Generally, SRMs are stored for extended periods of time, and transported from one place to another before ignition. Therefore, due to changes in environmental conditions and the transportation or handling procedure, SRMs are subjected to various environmental loadings during their lifetime, in which the temperature and loading rate play an important role (Yıldırım and Özüpek, 2011). Therefore, a successful grain design requires that each grain, regardless of its size, geometry and method of manufacture, must hold its shape over an extended range of temperatures and strain rates (Marimuthu and Nageswara Rao, 2013). In general, the common approach to assess the safety and reliability of SRMs is to analyze the structural integrity of the solid propellant grain, which generally includes two processes: conducting mechanical experiments and developing an accurate constitutive model that can precisely predict the complex behavior of propellant grains under various loading conditions.

Generally, a composite solid propellant, which is a typical viscoelastic material, is considered as polymer filled with solid particles. Such materials exhibit very complex behavior due to the damage process, which requires a wide range of tests to characterize. In recent years, the mechanical properties of solid propellants have been studied by

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numerous researchers because of their extensive use and specific engineering requirements. Schapery's group focused on developing the solid propellant nonlinear viscoelastic and viscoplastic constitutive equations that account for stress rate, internal state variables, temperature, and growing damage, and the developed constitutive equations have been widely used in finite element models (Farris and Schapery, 1973; Schapery, 1997; Schapery, 1999; Hinterhoelzl and Schapery, 2004). Özüpek compared several models and developed a constitutive model that gave the best representation of uniaxial tensile experimental data at room temperature under quasi-static loading (Özüpek and Becker, 1997). Jung studied composite solid propellants and developed a damage constitutive model based on elastic dewetting criteria and the softening effect to describe the nonlinear viscoelastic behavior obtained during stress relaxation tests in a temperature range of −90 °C to +60 °C (Jung et al., 1999). This model was later extended to three-dimensional cases, and implemented into finite element analysis (Jung et al., 2000). Chyuan numerically analyzed the structural integrity of hydroxyl-terminated polybutadiene (HTPB) propellant grains subjected to temperature loading (Chyuan, 2002), ignition pressurization loading (Chyuan, 2003a), and Poisson's ratio variation under ignition pressure loading (Chyuan, 2003b), using a constitutive model based on the static relaxation testing that employed the time–temperature superposition principle (TTSP) and reduced integration. Some recent studies have focused on the multi-scale constitutive behavior of solid propellants and have studied the effect of micro-structural damage evolution, such as the nucleation and propagation of damage along the particle–matrix interface (Matouš et al., 2007), and continuous void formation and growth (Xu et al., 2008), which was verified by uniaxial tension tests under low strain rates. Neviere conducted quasi-static tensile tests in the temperature range of −60 °C to +60 °C using TTSP to describe the non-linear viscoelastic behavior of HTPB (Nevière, 2006). Kalaycioglu simulated the extrusion process of a double base propellant, assuming the propellant to be elasto-vsicoplastic material, whose model parameters were determined by quasi-static uniaxial tensile tests (Kalaycioglu, 2010). Marimuthu simulated the structural integrity of propellant grains under inner pressure and gravity loading using static relaxation tests and the TTSP to specify the effective Young's modulus and Poisson's ratio (Marimuthu and Nageswara Rao, 2013). Moreover, Xu proposed a new method to obtain the relaxation modulus of HTPB propellants using the TTSP in temperature range of −50 °C to +35 °C (Xu et al., 2013). Han simulated crack propagation in HTPB propellants using a cohesive zone model in which the model parameters were obtained from quasi-static uniaxial tensile tests (Bo et al., 2012).

According to the aforementioned research, most studies have focused on static and quasi-static mechanical behavior. However, various types of loading conditions are imposed on propellant grains during the lifetime for SRMs, such as the occurrence of shocks during transportation, ignition pressure impact, and firing overload, which suggest that impact loading is one of the more critical conditions. Nonetheless, most propellant responses under high strain rate loading are not clearly understood. Zhang obtained low and high strain rate uniaxial compression curves for a nitrate ester plasticized polyether composition (NEPE) propellant for the first time over a temperature range of −40 °C to +40 °C, using a split Hopkinson pressure bar (SHPB) apparatus Zhang et al., 2014. After Kolsky (1949) introduced the SHPB technique for dynamic testing, SHPB apparatuses have been widely used to obtain the stress–strain responses of materials at high strain rates of around 10^2–10^4 s^{-1}, such as metals (Su et al., 2013), rocks (Liu and Xu, 2015), and composite materials (Matadi Boumbimba and Wang, 2012). As such, the high strain rate behavior of materials is generally evaluated experimentally by an SHPB apparatus. Owing to the scarcity of studies focusing on the dynamic responses of solid propellants, the experiments reported here were conducted to obtain the dynamic properties of a composite modified double-base (CMDB) solid propellant under uniaxial compressive loading. An SHPB apparatus was introduced to perform high strain rate testing. Moreover, a conventional universal testing machine was also employed to perform low strain rate testing. On the basis of suggestion that most SRM accidents have occurred in cold climate (Townend and Warren, 1985), the experiments here were conducted at low temperatures of −40 °C to 0 °C to obtain quantitative estimates of the effects of the strain rate and the temperature on the CMDB propellant.

2. Experimental methodology

2.1. Materials and sample preparation

A typical CMDB propellant consists of a double base binder (nitrocellulose and nitroglycerine), an oxidizer particle (ammonium perchlorate or RDX), a fuel particle (powdered aluminum) and some other additives for improving the bonding and burning characteristics. The material studied here is an RDX-CMDB propellant, wherein the RDX content is 54%, nitrocellulose is 20%, and nitroglycerine is 20.5% by weight. Cylindrical specimens were machined from the tubular propellant grain. To ensure the one-dimension stress requirement in axial direction during quasi-static testing, the aspect ratio (thickness/diameter) of the specimen was 1.5, where the diameter was 10 mm and the thickness 15 mm. To balance minimizing the interfacial friction effect against omitting the inertial effect in the specimen during SHPB testing, Davies has suggested that the best aspect ratio for a cylinder specimen is $\sqrt{3\upsilon}/2$, where υ is Poisson's ratio (Davis and Hunter, 1963). Moreover, Owing to that thick specimen is difficult to facilitate the stress equilibrium in the specimen, the aspect ratio of the cylindrical specimen for SHPB testing is 0.4 here, where the diameter was 10 mm and thickness 4 mm. After machining, both quasi-static and dynamic specimens were maintained at 50 °C over 24 h to remove residual stresses.

2.2. Quasi-static compression testing

The quasi-static compressive experiments for the CMDB propellant specimens were performed at three different