Chapter 10
Effect of Thermal and Mechanical Fatigue Loading on the Performance of Energetic Materials

Addis Kidane, Suraj Ravindran, Georgios Gavris, and Waiching Sun

Abstract Energetic materials widely used in defense and civilian applications are complex material systems incorporating binders, crystals, and other additives. Their failure mechanisms are complex and depend on many parameters, such as initial porosity, temperature, and loading rate. During service and transportation, the temperature and mechanical loading fluctuation can initiate and accumulate damage and degreed the material's mechanical strength. The effect of fatigue damage on the performance of energetic material needs to be better understood. This required understanding how the damage is accumulated in this material under different temperatures and loading conditions.

We propose a digital image correlation-based experiment to understand the mechanical and thermal fatigue damage accumulation in polymer-bonded energetic materials. This experimentation will be combined with first-principles physics-based multi-scale modeling to establish load-structure-damage-performance linkages for pressed and plastic-bonded energetic materials.

We used polymer-bonded sugar as a surrogate sample and subjected it to controlled fatigue and thermal loading. The microstructures of the sample before and after loading at different loading and thermal cycles are documented and used to study the damage accumulation. The virgin and damaged specimens are further exposed to high-strain loading, and their failure mechanism as a function of damage is also investigated.

Keywords Energetic materials · Thermal · Mechanical · Fatigue

Introduction

Energetic materials (EMs) such as explosives and propellants are designed for rapid energy release. However, thermal and mechanical fatigue can significantly impact their performance, compromising their stability and functionality under operational conditions. Thermal fatigue occurs when EMs are exposed to cyclic temperature changes, leading to the expansion and contraction of the material. This thermal cycling creates internal stresses, resulting in cracks or other forms of structural degradation. Over time, this can cause a decrease in the material's stability and energy release efficiency. Studies indicate that temperature fluctuations can accelerate the degradation of energetic materials, mainly through changes in molecular structure and composition [1, 2]

Mechanical fatigue involves repeated stress or strain on energetic materials, often through cyclic loading or impact. This repetitive mechanical stress can cause physical damage such as cracks, deformation, or delamination. As the material undergoes fatigue, its mechanical properties, including strength and elasticity, can deteriorate, leading to an increased risk of failure. Mechanical stress catalyzes the formation of defects, further compromising the integrity of the material [3-6].

The degradation process can accelerate when thermal and mechanical fatigue are applied simultaneously. The combination of thermal cycling and mechanical loading can lead to a faster breakdown of the material's structure, as these stresses interact and compound one another. The synergistic effects of these factors result in more rapid failure and greater performance loss, including diminished energy release and increased instability [7, 8]

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The combined thermal and mechanical fatigue significantly reduces energetic materials' operational lifespan and safety. As fatigue sets in, the material's reliability decreases, leading to potential safety hazards in practical applications such as propulsion systems and detonators. Improving fatigue resistance through new formulations, protective coatings, and enhanced manufacturing techniques can improve the safety of these materials.

Numerical and experimental works have been proposed to understand the failure mechanisms in energetic materials. Researchers, including our group, have developed experiment methods to measure the local deformation mechanism, the compaction wave propagation, and the effect of strain rate on the mechanical properties of energetic materials [11-16].

These studies have contributed to understanding failure in energetic materials, mainly polymer-bonded explosives (PBXs). However, these studies focused on dynamic and intermediate impact types of loading, and the fatigue life of energetic material is poorly understood. This work presents the effect of thermal and mechanical fatigue loading on the energic material response.

Experiment

Materials and methods

Materials and specimen preparation

This study uses polymer-bonded sugar (PBS) as a material system. Sugar has been widely used as a mechanical simulant of high-melting explosives (HMX). The specimens were prepared by cold pressing of prepreg sugar in a binder and plasticizer [16]. Cylindrical rods were first cold pressed, and cubic specimens were machined. Specimens were prepared carefully for digital image correlation measurement, as discussed in detail [16].

Experiment

A set of specimens was first subjected to cyclic loading, and the damage as a function of the loading cycles was captured. Each specimen was loaded under compressive cyclic loading at 60 % of the yield stress, and the moduli of the specimen as specified loading cycle was measured. The elastic modulus of specimens as a function of loading cycles tested at different loading frequencies is captured. A similar procedure was followed in the temperature cycle to measure the specimen's thermal fatigue damage as a function of the thermal cycle. A set of specimens with different damage as a function of loading and thermal cycle is produced. A fractography analysis of the specimen based on optical microscopy is used to distinguish different types of damage.

Once specimens were subjected to fatigue loading and sustained damage, a Hopkinson bar was used to test the specimens further. A range of specimens with different damage have been loaded under dynamic loading and were compared with virgin materials. The Hokinon bar was modified as a direct-impact gas gun to load the samples with a defined strain and strain rate loading. As shown in the figure, the specimen was attached to the transmitter bar, and a projectile was applied directly to the specimen.

The experiments utilize an ultrahigh-speed camera with microscopic and macro lenses, and a digital image correlation (DIC) technique in Fig. 1. The loading rate and the imaging frame were well synchronized to capture sufficient images during deformation. The digital image correlation data has been used to identify the damage initiation and programming and serve as input to the computational effort.

Computational

To capture the simulations of the crystal-binder interaction, the research group has developed a Material Point Method model to capture the therm-mechanical contact and the potential de-lamination of the crystal.

In the MPM model, the material point flows in the Eulerian background grid, enabling one to overcome the mesh distortion issue of the Lagrangian finite element while retaining the Lagrangian description of the history-dependent material behaviors (see Figure 2).

The modeling focuses on capturing the PBX behaviors by modeling the large-deformation behaviors of the binder, crystals, and the binder-crystal interface. We idealize the polymer binder as a Neo-Hookean material with a viscous response. While the volumetric responses are captured by a modified version of the Birch-Murnahan Equation of State, the dynamic shear modulus is rate-dependent.

The damage is modeled by a cohesive zone model explicitly written for the MPM framework. In the 2D setting, we introduce a cohesive element as massless line segments and assign the interface Lagrangian points. At each time step, the

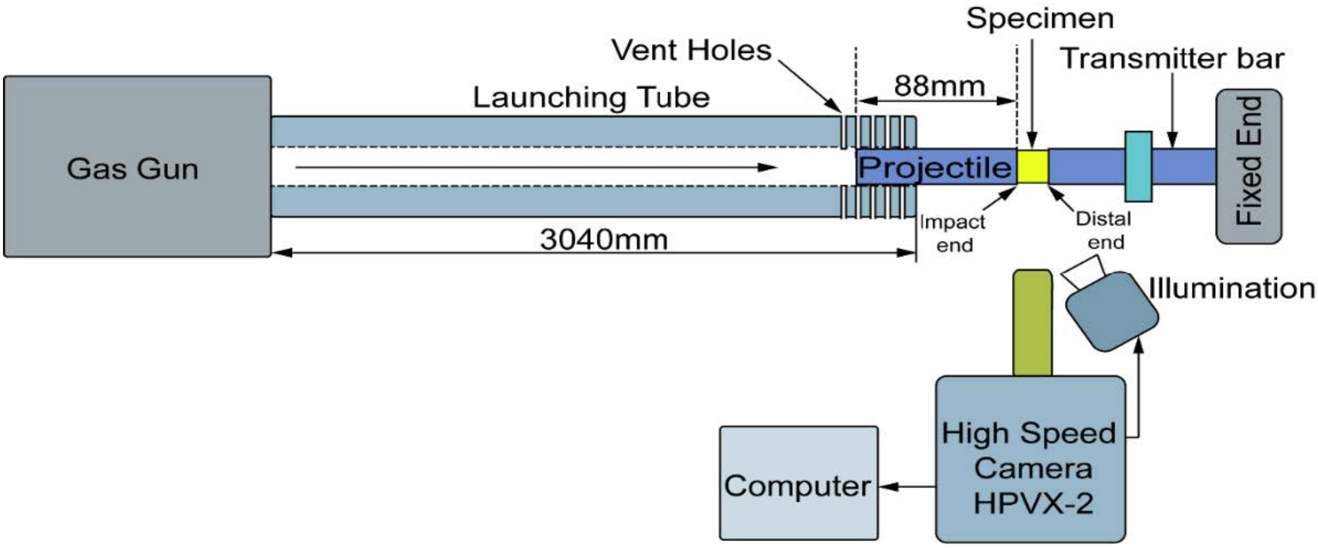

Fig. 1 Experiment setup

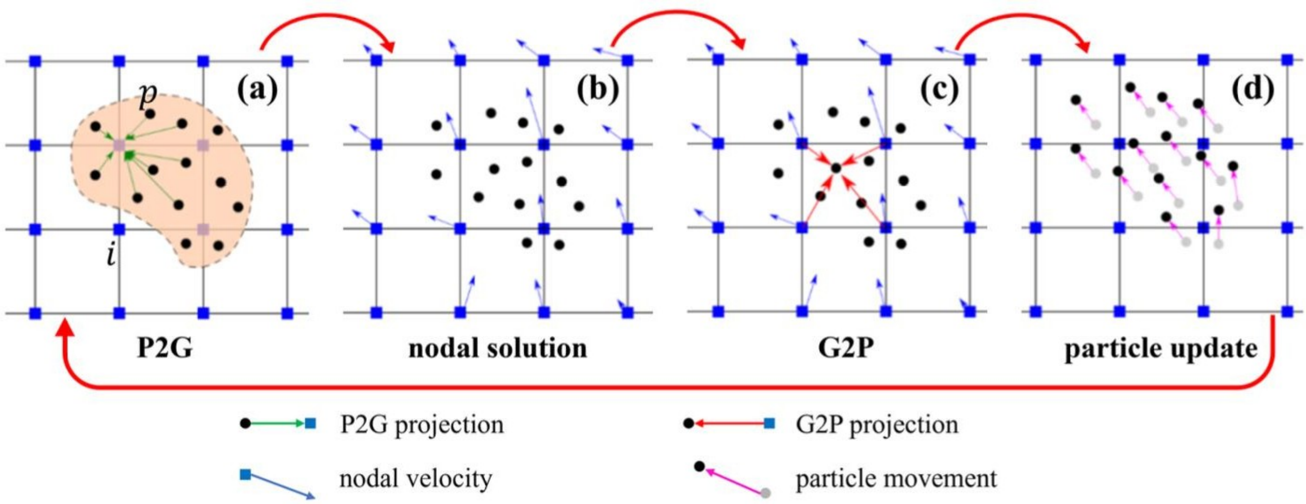

Fig. 2 MPM model description.

displacement between the two interfaces is projected in the Eulerian frame, and the relative displacement between the top and bottom interfaces is updated.

The cohesive zone model takes account of the mixed-mode contributions where an effective displacement is calculated as a weighted sum of the normal and tangential modes of deformation. Temperature dependence on the traction separation law is also captured (see Figure 3).

To capture the potential fracture triggered by the contacts of crystals, frictional responses under compression are also considered, and a contact algorithm is introduced so that the resultant hydrocode can capture the hot spot formation influenced by the frictional heating.

Results

A preliminary study on damage propagation was conducted by subjecting the damaged specimen to quasi-static and dynamic loading conditions. The microstructure image taken during the test indicates that the failure mechanism under quasi-static and dynamic loading differs. A complete fracture of the crystals has been observed in the quasi-static experiments. It is

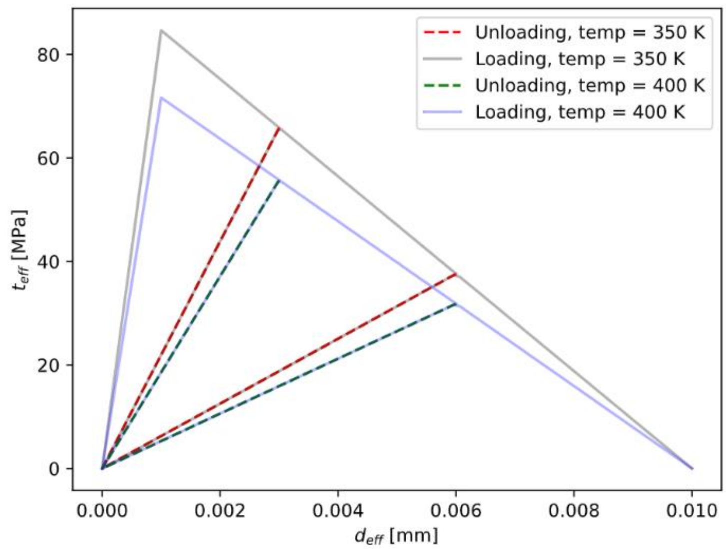

Fig. 3 Temperature-dependent traction separation law

more like a tensile fracture in the crystal and is expected from brittle material like sugar. On the other hand, the dynamic result shows a localized failure where the small crystal is squeezed between two relatively larger crystals. However, this localization is not everywhere but focused on small regions, usually where there is a sharp contact between crystals.

We also observed the high speed of the volume fraction of the crystal. The higher volume fraction material shows more heterogeneity and localization failure.

Conclusion

We have developed an experimental method to capture the effect of thermal and mechanical fatigue loading on the performance of energetic materials. Damage propagation as a function of the loading cycle has been studied; the damaged samples were tested under dynamic loading conditions and were compared with virgin materials. The generative AI enabled us to augment experimental data with synthetic data to meet the demand for more precise modeling.

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