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Research Progress on Material Creep Experiments

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ABSTRACT

Creep behavior in solid propellants, characterized by time-dependent deformation under constant load, critically impacts the structural integrity and operational safety of rocket motors. This paper reviews recent advancements in creep research across three dimensions: (1) Macro-meso characterization techniques, including innovative indentation methods and high-resolution micro-CT/SEM imaging, which elucidate damage evolution mechanisms such as pore nucleation and crack propagation; (2) Multi-factor influences, revealing temperature-stress synergies, filler-matrix interactions, aging effects, and loading-rate dependencies that govern creep dynamics; (3) Cross-material experimental progress, highlighting breakthroughs in cementitious materials (20% prediction accuracy improvement), soft matter rheology (80% testing acceleration), and polymer microstructure transitions. While current studies have established comprehensive creep databases and advanced constitutive modeling, challenges remain in understanding long-term damage accumulation and multi-physics coupling under extreme conditions. Future directions emphasize in-situ multi-scale monitoring, cross-scale computational frameworks, and AI-driven predictive models for next-generation creep-resistant materials.

KEYWORDS

Solid propellants; Macro-meso characterization; Multi-factor influence; Creep mechanisms; Creep-resistant design

1. INTRODUCTION

Creep, defined as the time-dependent plastic deformation of solid propellants under sustained mechanical loading, is a critical viscoelastic phenomenon with profound implications for the structural integrity of solid rocket motors (SRMs). Unlike instantaneous elastic or plastic deformation, creep evolves gradually over hours to years, driven by the complex interplay of molecular chain relaxation, filler-matrix interfacial slippage, and microstructural rearrangement within the propellant matrix. Under severe conditions, this slow deformation can culminate in catastrophic failures, such as debonding between the propellant grain and the motor casing—a pivotal interface that maintains structural confinement—and the nucleation and propagation of cracks under thermal or mechanical stress gradients. These defects compromise the motor’s load-bearing capacity, disrupt combustion stability, and ultimately lead to mission failure, particularly in long-term storage scenarios or during extreme operational environments (e.g., rapid temperature fluctuations, high-frequency dynamic loading).

Given that SRMs serve as the core power systems for strategic missiles, space launch vehicles, and other aerospace applications, ensuring their reliable performance over extended service lifetimes is of paramount engineering significance. Accurate characterization of propellant creep behavior—including its dependence on loading conditions, material composition, and environmental factors—enables the development of predictive constitutive models that underpin safety-critical design parameters, such as service life estimation, stress mitigation strategies, and manufacturing quality control.

This review synthesizes recent advancements in three interrelated domains critical to understanding and managing propellant creep. First, we explore the multi-scale mechanical characterization of creep, integrating macroscopic experiments (e.g., creep rupture tests, dynamic mechanical analysis) with mesoscopic investigations (e.g., scanning electron microscopy of deformation mechanisms, computational modeling of filler-polymer interactions) to decode the hierarchical links between microstructural features and bulk creep responses. Second, we dissect the multifaceted influences on creep kinetics, including temperature (via Arrhenius-type thermal activation), stress magnitude (linear vs. nonlinear creep regimes), moisture absorption (plasticizing effects on polymer matrices), and aging-induced chemical degradation (e.g., crosslink density changes, binder chain scission). Notably, synergistic effects between these factors—such as the combined impact of thermal cycling and sustained loading—are highlighted, as they often dictate failure modes in real-world applications. Finally, we survey creep studies across diverse propellant material systems, ranging from conventional composite propellants (e.g., ammonium perchlorate (AP)-based systems with hydroxyl-terminated polybutadiene (HTPB) binders) to advanced formulations like energetic thermoplastic elastomers and gel propellants, each presenting unique creep mechanisms due to differences in filler morphology, binder elasticity, and energetic component interactions.

By synthesizing these perspectives, this work aims to bridge fundamental material science with engineering practice, offering insights into how creep research can inform the design of more resilient solid rocket motor systems capable of withstanding the rigors of prolonged storage and demanding operational conditions.

2. ADVANCES IN MACRO-MESO CHARACTERIZATION OF CREEP MECHANICAL BEHAVIOR

Research on propellant creep relies on effective experimental methods, though existing studies remain limited and primarily focus on macro- and meso-scale investigations.

Macro-scale studies have systematically revealed deformation mechanisms under various loading conditions. Wang [1] identified a logarithmic-linear relationship between applied stress and creep failure time through constant-stress loading, cyclic tensile, and interaction experiments, with a damage accumulation model achieving <10% error. Bihari et al. [2] used dynamic mechanical analyzers (DMA) to demonstrate how spring constants and damping coefficients affect viscoelastic properties under varying stress and temperature. Zhang et al. [3] established a strain-rate equation for the secondary creep stage of double-base propellants via uniaxial tensile tests. Zhang [4] developed a viscoelastoplastic model for NEPE propellants by integrating generalized Kelvin and Saint-Venant models. Zheng Jian et al. [5] derived an exact Poisson's ratio expression for propellants using creep tests, while Shen Huairong [6] proposed a creep damage evolution model validated by uniaxial/biaxial experiments.

Meso-scale breakthroughs have emerged through advanced characterization techniques. Mei [7] innovated indentation methods for nondestructive mechanical testing, achieving macro-scale consistency. Liu et al. [8] applied indentation creep systems to study NEPE propellant curing kinetics, revealing quantitative relationships using the 2S2P1D model (goodness-of-fit >0.95). Wang Long's team [9] captured dynamic pore evolution via micro-CT, identifying exponential porosity growth beyond 5% strain. Li Chuntao et al. [9] correlated SEM/micro-CT data to establish a three-stage damage model (nucleation, propagation, failure) under constant load.

3. MULTI-FACTOR INFLUENCES ON PROPELLANT CREEP BEHAVIOR

Creep behavior is governed by complex interactions among temperature, stress, filler content, aging, and loading rates.

Temperature: Elevated temperatures accelerate molecular chain mobility and aging, reducing creep resistance [10]. Liu Shuang [11] demonstrated temperature-dependent creep in GAP-ETPE propellants, where generalized Kelvin models outperformed thermosetting counterparts.

Stress: Higher stress accelerates creep rates. Zhang et al. [12] linked stress levels to damage parameters, while Wu et al. [13] validated Burgers models for composite propellants. Wang et al. [14] confirmed logarithmic stress-failure correlations. Hu Yiwen [15] observed stress-temperature synergy causing high-temperature softening. Deng KW [16] defined four-stage creep in HTPB propellants during storage.

Fillers: Optimal filler content enhances creep resistance by restricting matrix flow [17-18], though excessive filler causes agglomeration [19]. Interactions (e.g., filler-asphalt [20], NC additives [22]) significantly modify performance.

Aging: Degradation and interfacial changes during aging alter creep behavior. Zhao et al. [23] observed CL-20/HMX co-crystallization effects, while Li Junke [25] reported aging-induced strength-ductility tradeoffs.

Loading rate: Finite loading rates improve parameter accuracy [26]. Yue et al. [27] noted hardening effects at higher rates, whereas Deng [28] highlighted strain-rate dependency in long-term storage.

4. ADVANCES IN CREEP TESTING ACROSS MATERIAL SYSTEMS

Cementitious materials: Haist et al. [29] improved concrete lifetime predictions by 20% via power-law corrections. Saeed’s XMPS theory [30] reduced drying shrinkage errors to <5%. Ismail [31] revised corrosion-permeability assumptions for coastal engineering.

Soft materials: Joshua’s stress modulation [32] enabled precise rate control (3 orders of magnitude), while Varun [33] accelerated clay rheology testing by 80% via time-temperature superposition.

Polymers: Shaukat [34] identified critical Tg±15°C transitions in polystyrene, linking creep compliance jumps (~50%) to relaxation dynamics.

Triaxial testing: Wei [35] and Lv [36] advanced Burgers model parameterization for red clay and asphalt, respectively. Collop [37] revealed stress-dependent viscous flow regimes.

5. CONCLUSION

Significant progress has been made in creep testing methodologies, multi-scale characterization, and mechanistic understanding. However, challenges persist in elucidating long-term dynamic responses of specialty materials (e.g., propellants) and multi-physics coupling under extreme conditions. Future research should prioritize in-situ multi-scale monitoring, cross-scale modeling integrating molecular dynamics and continuum mechanics, and AI-enhanced predictive frameworks to advance creep-resistant material design.

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