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High-strain-rate mechanical response of HTPE propellant under SHPB impact loading

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ABSTRACT
The high-strain-rate dynamic response of a hydroxyl-terminated polyether (HTPE) propellant during impact loading is essential for assessing the structural reliability and impact safety of HTPE propellant. In this study, a modified split Hopkinson pressure bar (SHPB) apparatus has been developed to research the stress–strain behavior of the HTPE propellant over strain rates ranging from 470 to 5910 s⁻¹ at room temperature, and the validity of the SHPB test is analyzed in detail. Meanwhile, the evolution of deformation to failure of the HTPE propellant was recorded by a high-speed digital camera synchronized with the SHPB test, which revealed the correlation between mechanical response and failure mode. Scanning electron microscopy was applied to investigate the microscopic failure mechanism of the post-test HTPE propellant, which indicated two characteristic failure modes: cracking propagates along the (1) debonding surface and (2) transgranular damage path.

INTRODUCTION
As the main energy sources of solid rocket motors (SRMs), solid propellants should withstand a series of severe impact stimulations, such as launch overload, fragment impact, and blast wave, to ensure operational safety and survivability of SRMs. Owing to the advantages of the high energy level and LOVA (Low Vulnerable Ammunition) feature, hydroxyl-terminated polyether (HTPE) propellants are widely considered as the next generation of solid propellants for novel tactical missiles. Therefore, in order to predict the reliability of HTPE propellants under impact loading well, studying the dynamic mechanical response of HTPE propellants is of crucial importance.

A HTPE propellant is a highly filled viscoelastic material, which is compounded with a polymeric binder (HTPE), crystal filler [e.g., ammonium perchlorate (AP)], and fuel particle [e.g., aluminum (Al)]. Generally, such viscoelastic materials exhibit very complex mechanical and damage characteristics under dynamic loading. So far, much attention has been paid on the issue of dynamic and quasi-static mechanical properties of solid propellants. Wang et al. conducted uniaxial tensile tests under strain rates ranging from 0.4 to 42.86 s⁻¹ by using an INSTRON testing machine, and the parameters for mechanical master plots of the HTPB propellant were obtained based on the time–temperature superposition principle (TTSP). Marimuthu et al. investigated the effective Young’s modulus and Poisson’s ratio of propellant grains under inner pressure and gravity loading through conducting a series of static relaxation tests. Yang et al. investigated the dependence of the strain rate on the mechanical properties of CMDB propellants in a wide scope of strain rates. From the experimental results, the Ree–Eyring model was proposed to capture the yielding phenomenon of CMDB propellants under strain rates spanning from 1.7 × 10⁻⁴ to 4 × 10⁵ s⁻¹. Sun et al. studied the mechanical properties of CMDB propellants under strain rates from 10⁻³ to 10³ s⁻¹ at temperatures from −40 °C to 0 °C, and the results indicated that the mechanical performance, such as yield stress, linear elastic modulus, and ultimate strain, depends upon the strain rate and temperature. Sunny et al. studied the strain rate sensitivity (SRS) of a HTPB based composite at ambient temperature, indicating a reduced rate sensitivity at strain rates higher than 2100 s⁻¹, which can be attributed to the abundant existing interfaces of filler beads/polymer binder. According to the previous work, the main fashion to research the dynamic mechanical response of solid propellants can be summarized as obtaining the stress–strain information at a specific loading rate followed by...
the development of mechanical constitutive models to predict the mechanical behavior under various loading conditions. However, the correlation between mechanical response and failure mode of propellants is still unclear. In addition, due to the relatively inadequate research relevant to impact response of HTPE propellants, the mechanical and failure mechanism of HTPE propellants under a high-strain-rate is not clearly understood, which is very important to assess the structural reliability of HTPE propellants.

In this study, a modified split Hopkinson pressure bar (SHPB) apparatus has been employed to research the stress–strain property of HTPE propellants under impact loading. The evolution from deformation to failure of HTPE propellants was recorded using a synchronized high-speed digital camera. Together with information from the stress–strain behavior and high speed images, the correlation between mechanical response and failure mode of HTPE propellants can be analyzed. The macroscopic and microscopic failure modes were revealed to probe the failure mechanism of HTPE propellants during dynamic loading. In addition, various SHPB tests of strain rates (from 470 to $5910\,s^{-1}$) were conducted to investigate the dependence of mechanical response of HTPE propellants on the strain rate, such as ultimate stress, strain energy density, and adiabatic temperature-rise effect.

**EXPERIMENTAL METHODOLOGY**

**Material and specimen preparation**

The prepared HTPE propellant specimen was fabricated in the process of normal casting, which consists of 55.0 wt. % AP as the oxidizer, 15.0 wt. % aluminum powder as the fuel, 12.0 wt. % HTPE as the binder, 12.0 wt. % N-butyl-N-(2-nitroxy-ethyl) nitramine (BuNENA) as the plasticizer, 1.5 wt. % isophorone disocyanate (IPDI) as the cross-linker, and 4.5 wt. % of other additives. The diameter of the AP particle was within the range of 100–200 μm, and the average size of the aluminum powder was $\sim20$ μm. After being cured in an oven at 50 °C for 120 h, the obtained HTPE propellant was machined into cylinders with 10 mm diameter and 6 mm length because this length/diameter ratio is good for reducing the effect of wave attenuation. The prepared sample of the HTPE propellant and its scanning electron microscopy (SEM) recording are depicted in Figs. 1(a) and 1(b), respectively. From Fig. 1(b), the homogeneous distribution of AP particles can be clearly observed in the polymer binder. Before SHPB testing, all samples were annealed at a temperature of 50 °C for more than 24 h to eliminate the residual stresses.

**Dynamic mechanical experiment using SHPB technology**

The SHPB technology has been universally developed to explore the stress–strain state of different kinds of materials under dynamic circumstances with high rate loading. In this study, a SHPB setup was built for conducting the dynamic experiments on the HTPE propellant samples, as shown in Fig. 2(a).

As depicted in Fig. 2(c), the main components of the SHPB apparatus contains a striker bar, an incident bar, and a transmitter bar; these three bars are all made of aluminum. In addition, the strain gauges are attached on the bars to measure the strain signals, and a high pressure gas gun is used for propelling the striker bar with a specific speed. With the geometry size of sample determined, the different loadings of the strain rate can be achieved by controlling the velocity of the striker bar. A layer of Vaseline between the sample and bars can minimize the friction effect. A high-speed camera was applied to capture the real time procedure within a SHPB test. Considering that the HTPE propellant is an energetic material, a protective box is used for security, as shown in Fig. 2(b).

In a SHPB experiment, the propagation of stress wave in bars is generally accompanied with wave dispersion, especially for the high frequency component of the stress wave. Herein, a small copper foil with a thickness of 1 mm was attached between the striker bar and the incident bar, serving as a pulse shaper. The goal of pulse shaping is to attain a status of dynamic stress equilibrium, accompanied with a constant-strain-rate response during the SHPB test. Based on the hypothesis of dynamic stress equilibrium, the functional relation between the strain rate, strain, and stress can be calculated from the strain signals of the incident and transmitter bar,
which is formulated as

\[
\begin{align*}
\dot{\varepsilon}_{\text{engi}} &= -\frac{2C_B}{l_s}\varepsilon_t, \\
\varepsilon_{\text{engi}} &= \frac{C_B}{l_s} \int_0^t \varepsilon_r dt, \\
\sigma_{\text{engi}} &= E_B \cdot \frac{A_B}{A_s} \varepsilon_t.
\end{align*}
\]

(1)

Herein, \(A_B\) is the cross-sectional area of the bars, \(C_B\) is the wave speed in the bars, and \(E_B\) is the Young modulus of the bars. The definition of \(C_B\) can be formulated as \(C_B = \sqrt{E/\rho}\), where \(\rho\) is the bar’s density, \(\varepsilon_t\) is the reflected signal strain, and \(\varepsilon_r\) is the transmitted strain signal. In addition, \(l_s\) is the initial length of the sample, and \(A_s\) is the initial cross-sectional area of the sample. For engineering materials, such as the HTPE propellant, the volume of the specimen is assumed to be constant during deformation. The functional relation between the true strain \(\varepsilon_{\text{true}}\), the engineering strain \(\varepsilon_{\text{engi}}\), the true stress \(\sigma_{\text{true}}\), and engineering stress \(\sigma_{\text{engi}}\) can be given as

\[
\begin{align*}
\varepsilon_{\text{true}} &= \ln(1 + \varepsilon_{\text{engi}}), \\
\sigma_{\text{true}} &= \sigma_{\text{engi}} (1 + \varepsilon_{\text{engi}}).
\end{align*}
\]

(2)

The incident, reflected, and transmitted signals captured in the SHPB test on the HTPE propellant are depicted in Fig. 3. The nearly rectangular shape of the incident and reflected stress wave indicated that the specimen deformed in a dynamic stress equilibrium status within a loading duration time of 200 \(\mu s\), while the strain rate was constant, which is determined as \(3550\ \text{s}^{-1}\). The nearly constant-strain-rate ensures the validity of experimental SHPB tests, which implies that the obtained stress–strain result gives a reliable description of the dynamic mechanical response of the HTPE propellant. Afterward, the microscope morphology of the post-test HTPE propellant was analyzed by SEM observation.

**RESULTS AND DISCUSSION**

**Dynamic mechanical response and fracture mechanism**

For the current SHPB tests, three repeated tests were conducted at each strain rate to ensure the reliability of the experimental result. As depicted in Fig. 4, the repeatability of three plots of the sample under strain rates ranging from 3530 to 3590 \(\text{s}^{-1}\) is good and the variance can be negligible, which verified the validity of the SHPB test.

As shown in Fig. 5, the plot of strain rate vs strain displays a nearly plateau region, which means an approximately constant-strain-rate loading during the SHPB test. Furthermore, the two plots of stress–strain and strain rate–strain share a similar strain domain,
damage in the HTPE propellant under SHPB testing. 27,28

strain and axial strain in the sample can be related to the degree of
between two bars and sustains a uniform deformation until a time
of 75 μs, accompanied with an almost constant stress level
with increasing strain (region III); in this region, crazes develop
into cracks and crushing of AP particles occurs, which results in
the loss in bearing capacity of the sample; in the end, the fracture
region corresponds to the decrease in stress, which means a complete
failure of the sample (region IV). In order to correlate the trans-
formation and stress–strain status of the HTPE propellant under
impact loading, the green numbers marked in the stress–strain curve
correspond to the numbers of the high-speed-records shown in
Fig. 6.

In order to reveal the real-time failure evolution of the HTPE
propellant under impact loading, a high-speed digital camera syn-
chronous with SHPB testing was used to record the deformation
procedure of the sample at a strain rate of 3550 s\(^{-1}\), as shown in
Fig. 6. From Fig. 6, it can be seen that the sample was sandwiched
between two bars and sustains a uniform deformation until a time
of 75 μs, which indicates the stress equilibrium in the sample. From
a time of 100 μs, the transverse strain of the sample increases signifi-
cantly, which implies a prominent lateral tensile stress in the sample
normal to the axial loading direction, and induces cracking along the
axial loading. Finally, a complete failure of the sample can be seen at
200 μs, which resulted in a rapid decrease in stress.

As a typical viscoelastic material, the relation of transverse
strain and axial strain in the sample can be related to the degree of
damage in the HTPE propellant under SHPB testing. 27,28 Figure 6
shows the relation of time vs axial and transverse engineering strain
during the SHPB test at 3550 s\(^{-1}\). The axial engineering strain can
be obtained from the SHPB test using a strain gauge. During the
whole deformation, the axial strain of the sample exhibits a lin-
early increasing relationship with time, which indicates an almost
constant-strain-rate loading, and the slope of the linearly growth
relation can be defined as the strain rate (3550 s\(^{-1}\)). On the other
hand, the transverse engineering strain can be measured from high
speed camera recordings. There exists an obvious inflection point
at 75 μs from the plot of transverse strain vs time, which can be
attributed to the initiation of debonding and crazing. After 75 μs,
the increasing rate of transverse strain becomes faster than that of
axial strain, which means the volume expansion induced by dam-
age of the HTPE propellant under impact. In the region from 75
to 160 μs, a nearly linearly increasing transverse strain implies a
stable crack propagation and crushing of AP particles. Combined
with the information from Figs. 5–7, the compressive response of
the HTPE propellant under impact loading can be concluded as an
initial homogeneous deformation without damage, followed by a
debonding and crazing process with a rapid growth in lateral strain,
then a stable crack propagation and crushing of AP particles with a
steady stress level, and finally a complete failure with fragmentation
of the HTPE propellant.

Figure 8 depicts the schematic illustrations of the failure evo-
lution for the HTPE propellant under the SHPB test at a strain rate
of 3550 s\(^{-1}\). Initially, the cylindrical sample deforms under impact
loading without damage [see Fig. 8(a)]. With continued impact load-
ing, the crazing process initiates in two forms: axial crazing on the
side of the cylindrical sample parallel to the loading direction and
circumferential crazing on the end face of the cylindrical sample
perpendicular to the loading direction [see Fig. 8(b)]. On further
increasing the strain, multiple crazes converge into cracks in the
sample, forming axial cracks initially and circumferential finally,
which means that the HTPE propellant has completely failed. The
damage morphology of the HTPE propellant depends on the ampli-
tude of the strain rate. Under a low strain rate (470–880 s\(^{-1}\)), no
FIG. 8. Schematic diagram of the failure evolution for the HTPE propellant under the SHPB test at a strain rate of 3550 s$^{-1}$: (a) the original cylindrical sample without damage, (b) initiation of crazing under impact loading in forms of axial mode and circumferential mode, (c) development of crazes into cracks under further impact loading, and (d) photographs of axial cracks and circumferential cracks.

obvious damage can be seen because the energy input is not enough to fracture the specimen. When the strain rate increases to the order of 2000 s$^{-1}$, the circumferential and radial crazes initiate on the end surface of the specimen and develop into the inner structure. As the strain rate increases to 3550 s$^{-1}$, macroscopic circumferential and axial cracks propagate through the whole specimen, resulting in a final fracture, as depicted Fig. 8.

Furthermore, the SEM observation was conducted to study the microscopic damage mechanism of the HTPE propellant at a strain rate of 3550 s$^{-1}$. From Fig. 9, it can be seen that two characteristic failure modes caused by SHPB loading can be found: (1) cracking propagates along the debonding surface [see Fig. 9(a)] and (2) cracking propagates along the transgranular damage path [see Fig. 9(c)]. From the zoomed-in image of the debonding surface [see Fig. 9(b)], a rough surface of the HTPE matrix can be seen, indicating a typical ductile failure. As shown in Fig. 9(d), a smooth cleaving surface of the AP particle implies a more rapid cracking speed, resulting in brittle failure. In a few words, the compound damage modes of the HTPE propellant can be attributed to the high strain energy input by high strain rate loading.

Quantitative analysis of strain rate dependence on mechanical behavior

To analyze the strain rate dependence on mechanical behavior of the HTPE propellant, a series of SHPB experiments at different strain rates from 470 to 5910 s$^{-1}$ were conducted at 20 °C, as shown in Fig. 10. Both ultimate stress, $\sigma_m$, and ultimate strain, $\varepsilon_m$, increase with the strain rate, which means that the HTPE propellant is a rate-dependent material. Overall, all stress–strain curves behave as a typical rubber feature, without an obvious yielding point, and these plots with a similar profile implies that the HTPE binder dominates the mechanical response of the HTPE propellant. From Fig. 10, it can be seen that a prominent plateau domain can be revealed in the curves of strain rates from 1650 to 5910 s$^{-1}$, whereas in the case of a lower strain rate, 470 and 880 s$^{-1}$, the stress gradually increases with strain, followed by a rapid decline in stress, and no obvious plateau domain can be noticed. The probable reason can be that under high strain rate loading, cracking of the HTPE binder and crushing of AP particles may lead to a plateau domain accompanied with a moderate increase in stress, while under low-strain-rate loading, the energy input is insufficient to fracture the specimen. Herein, the strain energy density (U), can be defined as the area below the stress–strain plot.

The strain rate dependence of the HTPE propellant on mechanical properties (such as ultimate stress and strain energy density) was
FIG. 11. Strain rate dependence of the HTPE propellant on (a) ultimate stress and (b) strain energy density across the strain rates from 470 to 5910 s\(^{-1}\).

where \( \eta \) is the conversion ratio of strain energy to heat in the adiabatic heating process, which can be assumed as 0.95; \( \rho \) is the density of the sample, 1770 Kg/m\(^3\); and \( c \) is the specific heat, 1650 J/(Kg K). Considering that the strain energy density, \( U \), can be illustrated by \( U = \int_0^\infty \sigma(\varepsilon) d\varepsilon \), Eq. (5) can be transformed to \( \Delta T = 0.0257 \dot{\varepsilon}^{0.56} \). Therefore, with the increase in the strain rate, the temperature increase in the HTPE propellant becomes higher, which implies that the softening effect on the HTPE propellant induced by adiabatic temperature-rise becomes more pronounced under a higher strain rate.

CONCLUSIONS

In order to predict the structural reliability and impact safety of HTPE propellant well, the dynamic response of HTPE propellant was studied over strain rates spanning from 470 to 5910 s\(^{-1}\) by using a modified SHPB setup. The following remarks can be achieved.

By optimizing the arrangement of the SHPB setup, the validity of experimental results were verified. Together with the information from the stress–strain curve, high speed records, and axial/transverse strain analysis, the compressive response of the HTPE propellant under impact loading can be clarified as an initial homogeneous deformation without damage, followed by a debonding and crazing process with a rapid growth of lateral strain, then a stable crack propagation and crushing of AP particles with a steady stress level, and finally a complete failure with rapid dropping of stress.

Macroscopically, the failure of the HTPE propellant is displayed in two forms: the axial cracking parallel to the loading direction and the circumferential cracking perpendicular to the loading direction. Microscopically, two characteristic types of microcracks can be revealed: cracking propagates along (1) the debonding surface and (2) the transgranular damage path.

Based on the assumption that a part of the strain energy can be converted into heat,\(^{31,32}\) the adiabatic temperature-rise of the tested HTPE propellant can be calculated as

\[
\Delta T(\varepsilon, \dot{\varepsilon}) = \frac{\eta}{\rho c} \int_0^\varepsilon \sigma(\varepsilon) d\varepsilon,
\]

where \( \eta \) is the conversion ratio of strain energy to heat in the adiabatic heating process, which can be assumed as 0.95; \( \rho \) is the density of the sample, 1770 Kg/m\(^3\); and \( c \) is the specific heat, 1650 J/(Kg K). Considering that the strain energy density, \( U \), can be illustrated by \( U = \int_0^\infty \sigma(\varepsilon) d\varepsilon \), Eq. (5) can be transformed to \( \Delta T = 0.0257 \dot{\varepsilon}^{0.56} \). Therefore, with the increase in the strain rate, the temperature increase in the HTPE propellant becomes higher, which implies that the softening effect on the HTPE propellant induced by adiabatic temperature-rise becomes more pronounced under a higher strain rate.

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\[
\Delta T(\varepsilon, \dot{\varepsilon}) = \frac{\eta}{\rho c} \int_0^\varepsilon \sigma(\varepsilon) d\varepsilon,
\]
adiabatic temperature-rise effect was quantitatively analyzed by fitting an empirical power law function.

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The authors declare that they have no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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