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Compressive Mechanical Property Tests for Energetic Material Hazard Sensitivity

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Threat stimuli to propulsion systems lead to a broad range of responses depending on several factors, one being loading rate and its influence on energetic materials compressive behavior. This article reviews techniques for characterizing the mechanical properties of energetic materials and the significance of those properties to the material's hazards sensitivity. Small-scale hazards test devices and conventional mechanical properties testers would preferably simulate the loading conditions of the high-rate insensitve munitions (IM) tests but often fall short of this goal. The strain rate ranges of these tests are compared, and in cases where their strain rate capabilities do not adequately extend to IM ranges, low-temperature testing techniques are reviewed which expand their useful rates. Next, several newer compressive mechanical properties test devices are reviewed which have significantly higher strain rate range capabilities than the conventional test devices. By incorporating the low-temperature testing techniques, their capability to simulate higher rate IM regimes is shown. Finally, a comparison is presented of how material properties vary as a function of strain rate and temperature, using data obtained with these newer test devices.

Introduction

PRESENT-DAY weaponry contains encased energetic materials, frequently both in the form of propellant for controlled propulsion of ordnance and explosive for the warhead. By their nature, these materials are hazardous to process, transport, store, and then finally use for their intended purpose. Their sensitivity to unwanted reaction can also be related to combat vulnerability, which to some extent is addressed by the insensitive munitions (IM) program.[1,2] Within the next few years, fielded munitions must pass a series of IM tests in which the worst case result in burning of the material only.

The response of the complete system must be considered to obtain the required understanding of its failure potential in the above scenarios. For example, bullet impact can lead to no reaction, violent deflagration, or full-scale detonation depending on the thickness and type of casing, the type of the energetic material,[3] bullet size, shape, and velocity, ambient temperature, degree of confinement, rate of deformation of the energetic material, etc. These numerous variables make determination of the real mechanism for an accident difficult to quantify. However, it is clear that accurate material property characterization is needed in two integral parts of a propulsion system, the energetic material and the casing, in compressive stress fields with large plastic strains and high loading rates. Harding[4] contains information on high strain rate mechanical properties of materials which are used as casings. Mescall[5] also discusses casing material properties under compressive loadings and summarizes tests for obtaining these properties including the upset test and the Taylor test.

In this article we will focus on the mechanical property characterization of the energetic material and the role mechanical properties play in energetic material hazards sensitivity. An understanding of the threat/response relationship for the energetic material will help identify materials which give acceptable systems—level IM properties. For example, in samples of brittle explosives (TNT and composition B) impacted with projectiles, Wiegand[6] showed that when confined, the materials fail by yield and plastic flow, while fracture and crack propagation are inhibited. However, as confinement is decreased, failure occurs by fracture and crack propagation. He concluded that the probability or ease of ignition is greater when confinement leads to failure by yield or plastic flow rather than fracture.

Connor[7] studied the response of energetic materials (cased and uncased) as a function of impact velocity. Fragments were fired at impact velocities as high as 2500 m/s into a confined explosive sample. Relatively brittle explosives showed a steady rise in violence of response with increasing impact velocity. In contrast, plastic bonded explosives showed little impact velocity sensitivity until a critical velocity (or strain rate) was reached. For unconfined explosives it was suggested the only stimulus which could lead to initiation is a high-rate shock which puts the explosive in a high hydrostatic state of stress. However, from projectile impacts on various barrier thicknesses, Connor[7] observed detonations at barrier thicknesses too great to allow primary shock wave transmission into the explosive. This suggests there is also a nonshock mechanism responsible for the detonation. Thus, for confined explosives, rapid plastic working of the explosive near the impact site due to projectile penetration was postulated to lead to local initiation. The confinement caused a greater pressure buildup which increased the violence of the reaction.

Development of a protocol to access the hazards of munitions subjected to projectile impact is under way, but emphasizes only the shock initiation mode.[7,8] First, the stimulus is described, which with the casing material properties and geometry determines the shock in the case. Hugoniot properties are required for calculating the shock in the energetic material. Finally, to determine the possibility of detonation, generally shock initiation criteria are needed. However, the shock to detonation transition data available do not address the role of mechanical properties, specifically the degree and type of damage produced in the energetic material by the impact, and the degree to which the damaged energetic material is more susceptible to ignition.

Other sensitivity tests, such as the drop-weight impact hazards test,[9] have been created as small-scale screening tools

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for explosives and propellants, and are now used to define insensitive energetic materials. These laboratory tests approach the vulnerability issue from the viewpoint of accidental initiation, which may occur in manufacturing and/or handling of energetic materials. Ideally, such tests would define the energetic material hazard response as a function of the magnitude, duration, and initial rate of the applied stimulus over a broad range of values.

Another set of small-scale tests is used to characterize various energetic materials mechanical properties in either tension or compression. Because the latter are thought more relevant to mechanical IM stimuli such as bullet impact, one goal of the present study is to highlight strain rate range deficiencies of common compressive mechanical properties test methodology. For example, Instron testing in compression at maximum crosshead speed subjects the sample to strain rates that fall well below both those of small-scale mechanical hazards tests such as the drop-weight test, and those of the IM tests such as bullet impact. One method to simulate higher rates in mechanical property determinations is the use of lower temperatures. The cold temperatures put the energetic material in a brittle state, as does the high rate. Therefore, another goal of this work is to review various shifting techniques, which relate properties measured at the cold temperatures to those obtained at high rates and vice versa, specifically for nonlinear, viscoelastic energetic materials.

Our final goal is to compare several new tests which have been designed to measure the dynamic compressive properties of energetic materials loaded uniaxially and biaxially, in some cases from load application to ignition. These tests thus potentially couple the small-scale properties determination with hazards sensitivity information. By combining these new higher rate testers with low temperature testing and then applying the shifting techniques, both mechanical properties and laboratory-scale hazards response can be obtained at rates that approach the IM test levels.

Characterization of Mechanical Properties

The possible threats to a munition fall into three broad categories: 1) thermal (T), 2) mechanical (M), or 3) electrical (E). For example, insensitive munitions tests fall into the first two categories: bullet or fragment impact (M), shaped charge jet impact (M), and fast and slow cookoff (T). Electrostatic discharge ignition testing methodology (E) is not yet developed, and is currently a small-scale procedure for energetic materials, as opposed to munition systems. In general, however, the type of energy delivered to the energetic material may not be as important, from a hazards standpoint, as the amount per unit energetic material area (or volume) and the rate and duration of load application.[10]

Small-scale hazards tests define reponse to shock, impact, friction, etc. Focusing on these stimuli, Fig. 1 shows qualitative mechanical load vs time curves which suggest that the initial rate of application (dP/dt) increases by three orders of magnitude from frictional loading to impact loading, and by eight orders of magnitude from friction to shock loading. Magnitudes for loads resulting from these stimuli also increase in this order. The failure mechanisms of energetic materials are significantly different for these three distinct loading stimuli as explained below.

Strain Rate Categorization

An alternative way of characterizing threat regimes is the strain rate imparted to the energetic material. Table 1 lists four general strain rate ranges ($\dot{\varepsilon}$) into which different mechanical stimuli fall, experimental techniques for testing in these ranges, and the corresponding hazards and/or IM tests. For impact-type loading (Fig. 1), stimulus pressures of O(10 MPa) over duration of O(0.1 ms) occur. This combination results in a medium strain rate stimulus which could describe a threat such as a low level impact of a missile falling to the

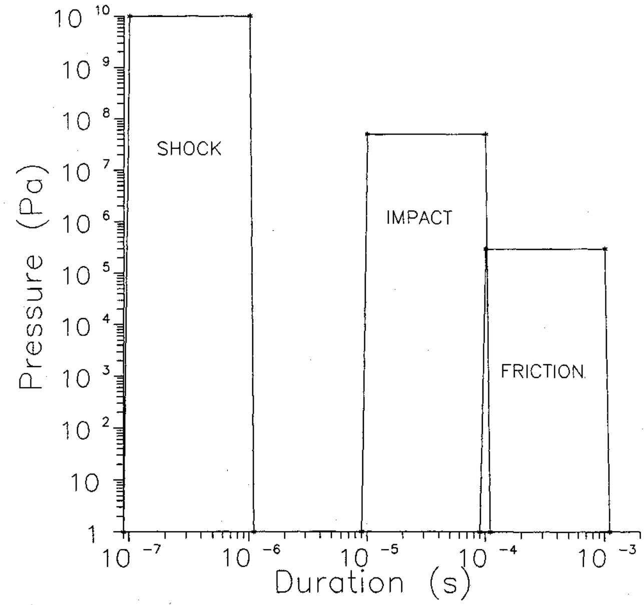

Fig. 1 Qualitative mechanical load vs time curves for three stimuli used in small-scale hazards tests.

deck of an aircraft carrier. For shock or very high loadings, the stimulus pressures are of O(10 GPa) and duration of O(μs). Threats in this very high strain rate range could include hypervelocity fragment impact and shaped charge jet impact.

Each properties test method is typically performed over a limited range of strain rates, due to experimental limitations, as shown in Table 1.[11] Techniques do exist, however, for simulating the stress state at high (or low) strain rates by testing at low (or high) temperatures. Equations are discussed below which use a shifting technique to provide a means of temperature/strain rate conversion. Therefore, if mechanical properties can only be obtained from tests at a single strain rate but over a range of temperatures (or vice versa), values at other strain rates (or temperatures) can be determined. In one technique, stress relaxation tests are performed on the energetic materials, and using the theory of time/temperature superposition, tests at different temperatures simulate different strain rate ranges.

Time/Temperature Superposition

In stress relaxation tests, a material is pulled to a certain strain level and held at that strain level while the load level is measured over a period of time. These tests are typically done at several different temperatures. The data at the different temperatures are then shifted manually to give a smooth curve, and a shift factor (a_t) is found for each temperature. The actual test times are then divided by the corresponding shift factor, and the results are plotted as in the master modulus curve of Fig. 2 which is for a hydroxy terminated polybutadiene (HTPB) propellant.[12] This transformation follows the Williams, Landel, Ferry[13] (WLF) equation

$$\log a_t = C_1(T - T_g)/(C_2 + T - T_g) \tag{1}$$

where C_1 and C_2 are constants for a given material, T is the temperature of the actual test, and T_g is the glass transition temperature of the material.

Noting that the x axis is in seconds, the inverse can be interpreted as a strain rate. The corresponding strain rate ranges from Table 1 are also shown in Fig. 2. The shape of the curve provides insight into the state of the propellant at various strain rates. At low strain rates or high temperatures, the propellant behaves in a ductile manner. In this range, yield and plastic flow are likely mechanisms of failure. It is known that the master modulus curve eventually levels off

Table 1 Strain rate range classification

Description	Strain rate range,[a] s^{-1}	Experimental techniques	Hazard and/or IM tests
Low	$\dot{\varepsilon} < 10^{-1}$	Instron	na
Medium	$10^{-1} < \dot{\varepsilon} < 2 \times 10^{2}$	Servohydraulic tester, drop test	Drop weight impact test
High	$2 \times 10^{2} < \dot{\varepsilon} < 10^{4}$	Hopkinson bar, Taylor test	Bullet impact, drop weight impact test
Very high	$\dot{\varepsilon} > 10^{4}$	Flyer plate, wedge tests	Fragment impact, shaped charge jet impact, card gap

[a]After Follansbee.[11]

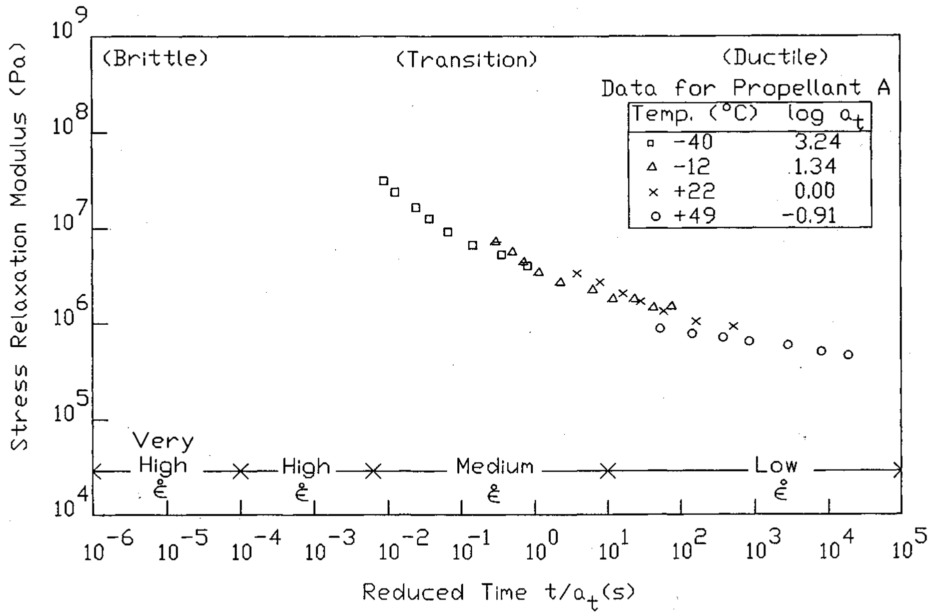

Fig. 2 Stress relaxation master modulus curve for HTPB propellant (after Francis[12]) showing how propellant stress state changes at different strain rates.

when the material reaches a strain rate corresponding to its glass transition temperature.[14] Thus, at high strain rates or low temperatures, the propellant behaves in a brittle manner. Fracture is the likely mechanism of failure in this range. Therefore, an explosives research performing gas gun tests might find fractured samples after a test if the material did not react. In the transition region between these two extremes, the material behavior is more difficult to quantify. Further, Wiegand[6] shows the effect of confinement.

Lindholm[15] also uses a strain rate/time inversion technique, but based upon 1% strain in the sample. Therefore, he does not show an exact inverse relationship between time and strain rate as in Fig. 2, but rather a two order of magnitude difference. However, the general argument of high strain rates corresponding to low characteristic times (and vice versa) still applies.

Depending upon which small-scale mechanical properties test is used, the material will respond differently. The propellant data in Fig. 2 were obtained in a low-rate Instron machine, but at different temperatures. The low-temperature Instron data (−40°C) "shift" to the medium strain rate regime illustrating how temperature changes relate to strain rate ranges and that temperature variations of tests using these devices can significantly broaden their applicability.

The validity of time-temperature-rate equivalence for compression was established recently by Lieb and Leadore.[16,17] Stress relaxation tests were performed on gun propellants over the temperature range of −40 to 60°C and the corresponding master curves and shift factors were determined.[16] Then mechanical response measurements were taken of these gun propellants in compression over a range of strain rates (0.1–100 s^{-1}) and at the corresponding temperatures which were predicted to result in an equivalent mechanical response. Essentially identical mechanical property values were obtained for each propellant tested under equivalent temperature-rate conditions.[17] This equivalence held both in the strain region of the stress relaxation measurements and, more importantly, in the strain regions corresponding to failure.

Connor[7] has observed a correlation between severity of response and the strain-rate-adjusted glass transition temperature for several confined propellant specimens subjected to projectile impact. Below this temperature explosion occurred, whereas above, only burning resulted in these tests. Higher strain rates result in increased strain-rate-adjusted glass transition temperatures, and here we note that for the three propellants tested, the value (at 1.67×10^{4} s^{-1}) was nearly 30°C higher than at the lower strain rate of 1.67×10^{-2} s^{-1}.

Compressive Mechanical Properties for Energetic Materials

Lieb et al.[18] argue that the propellant mechanical response after compressive failure has occurred is of prime importance to severity of response in hazard scenarios, because exposed fracture surface area (for brittle materials) promotes increased combustion and, hence, a more violent reaction. Therefore, they propose a set of compressive failure parameters as illustrated in Fig. 3.

The compressive modulus (E_c) is defined in the conventional manner as the slope on the linear portion of the stress/strain curve. Material failure is defined at the point where the second derivative of the stress with respect to strain is minimum, σ_{max} in Fig. 3, since this is the point where the material loses strengh most rapidly.[18] This failure stess (σ_f) occurs at some point after the yield stress (σ_y). However, it should be mentioned that "yield" as defined for energetic materials is not the same as for a metal. If the energetic material is in a brittle state (due to cold temperature or high strain rate) its yield behavior is similar to a metal. But if the energetic material is in transition to/or ductile, the polymer

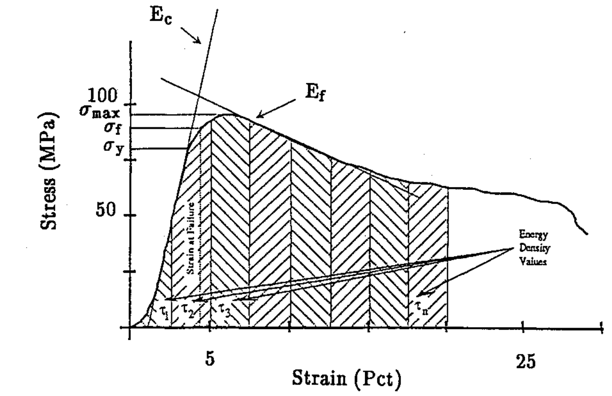

Fig. 3 Definition of compressive failure parameters from Lieb et al.[18]

chains are able to store energy and perhaps break, leading to strain-rate-dependent stress-strain curves.

The failure modulus (E_f) characterizes the postyield material response and measures how rapidly the material is losing (or gaining) strength. Brittle failure results in a high E_f, whereas ductile failure is characterized by a low, or even negative E_f. A normalized failure modulus (NFM $= E_f E_c$) is defined to distinguish mechanical damage effects from the initial strength of the material. Lieb also reports the incremental energy density (τ_n) which represents the amount of energy/unit volume absorbed during a strain interval. The incremental energy density monitors the material's ability to absorb energy; when fracture occurs, τ_n decreases significantly with the generation of undesirable surface area.

Temperature/Strain Rate Conversion

Ho and Fong[19] used a modified split Hopkinson pressure bar (SHPB) to obtain stress-strain information for a series of composite and double-base propellants over a large range of temperatures (-60 to 50°C) but small range of strain rates (5–25 s^{-1}). They found yield stress vs logarithmic strain rate (Fig. 4) gave linear relationships for all propellants at all the temperatures. The lines at the different temperatures are nearly parallel except at temperatures >40°C. This allowed Ho and Fong to shift the data in a technique similar to the time/temperature shift discussed above so that all data lie on one composite curve, and supports the idea that increasing (or decreasing) the temperature has the same effect on the yield stress as decreasing (or increasing) the strain rate imposed on the sample. An empirical equation was determined for yield stress

$$\sigma_y = K_1 + K_2 \log(\dot{\varepsilon} a_t) \qquad (2)$$

where K_1 and K_2 are constants. This equation is analogous to the temperature/strain rate conversion discussed earlier: yield stress at a selected temperature over a large strain rate range can be predicted from data in a smaller strain rate range at a selected number of temperatures and vice versa. K_2, which is the slope of the logarithmic curve, indicates the material's temperature and strain rate sensitivity.

For example, Ho and Fong[19] found a high K_2 value for a cast double base (CDB) propellant, which indicates the yield stress increases sharply with decreasing temperature and increasing strain rate. On the other hand, HTPB/ammonium perchlorate (AP) propellant had a low K_2 value, suggesting less sensitivity to temperature and strain rate compared to a CDB material. Ho and Fong explain these results by noting that the HTPB/AP glass transition temperature is outside of the range of temperatures tested. However, the glass transition temperature for the CDB propellant (11°C) was within the tested range. They feel if the relationship between the glass transition temperature and K_2 is valid, the loss spectra (from dynamic mechanical-thermal analysis) for other materials could be used as a guideline for determining the applicability of Eq. (2) at selected temperatures or strain rates. If the material properties vary in a consistent manner over a large range of strain rates and temperatures, extrapolation of equations such as Eqs. (1) and (2) can be accomplished with a higher level of confidence.

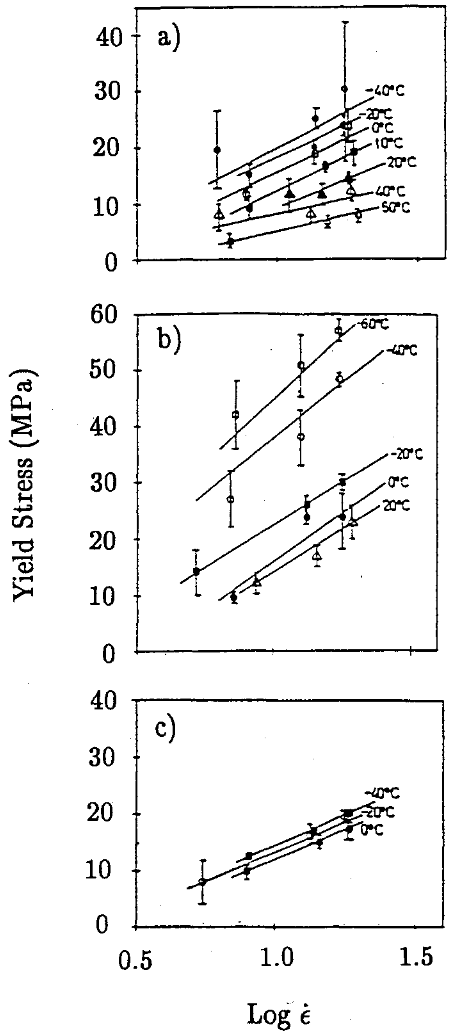

Fig. 4 Yield stress vs logarithmic strain rate at different temperatures for a) CDB, b) GAP/AP, and c) HTPB/AP. The parallel linear relationship allows the curves to be shifted thus collapsing the data on one master yield stress curve. From Ho and Fong,[19] appeared as Fig. 10, used with permission of Chapman & Hall, London.

Strain Rate Sensitivity Exponent Technique

The yield stress vs strain rate curves at room temperature for a steel and a softer material (JA2 gun propellant) both show a linear relationship in Fig. 5 over a large range of strain rates. From this log-log representation a constant strain rate sensitivity exponent N is obtained from the inverse slope of the line[20]:

$$N = (\Delta \log \dot{\varepsilon} / \Delta \log \sigma_y)_{T,\varepsilon} \qquad (3)$$

Kassner and Breithaupt[20] argue that since the steel response is similar at high and low strain rates, the controlling mechanism of plastic deformation (thermal activation of dislocations over short range barriers) is also the same at both levels.

The rate-controlling mechanism for plastic flow is also the same over a large range of temperatures, but at two different strain rates (Fig. 6). At a selected temperature, the increase in the yield stress from the low to high strain rates is given by Eq. (3).

Table 2 Predicted yield stress of GAP/AP at 17 s^{-1} from 8 s^{-1} data using strain rate sensitivity exponent Eq. (3) and modified Eq. (4)

	−40°C			0°C			20°C			50°C		
	Eq. (3)	Eq. (4)	Exponent	Eq. (3)	Eq. (4)	Exponent	Eq. (3)	Eq. (4)	Exponent	Eq. (3)	Eq. (4)	Exponent
Yield stress, MPa	196	61	49	80	25	29	72	23	23	65	20	18

T_g for GAP/AP is −30°C.[19]

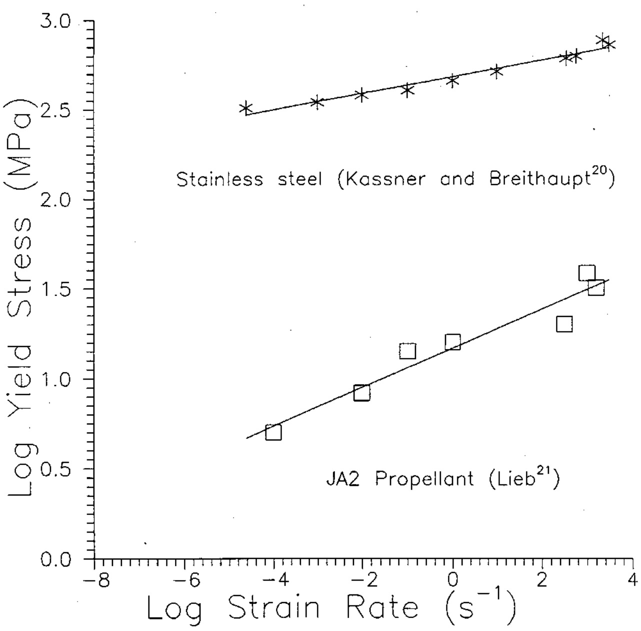

Fig. 5 Log stress vs log strain curves for stainless steel[20] and JA2 propellant[21] showing constant strain rate sensitivity over large strain rate. Data for steel obtained using a Hopkinson bar.

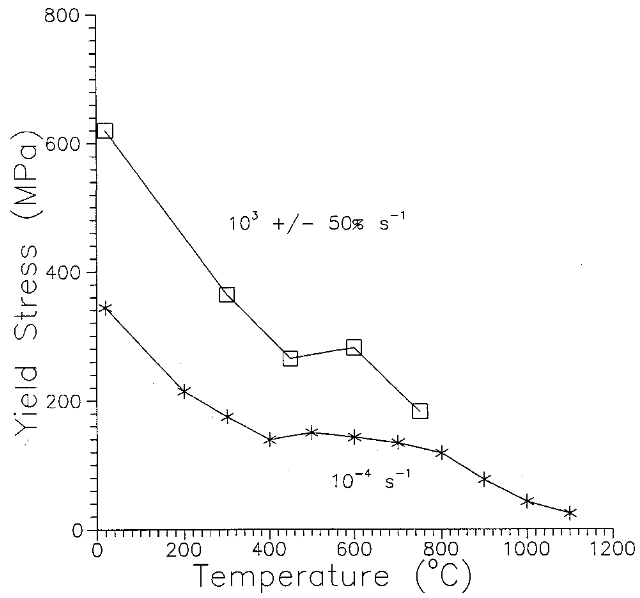

Fig. 6 Yield stress as a function of temperature at high and low strain rates. The similar shape of the curves indicates the strain rate exponent equation can predict the response at higher rates from data at lower rates. Data shown are for steel.[20]

The applicability of Eq. (3) to rocket propellant was investigated using data from Ho and Fong[19] for glycidyl azide polymer (GAP)/(AP) propellant. Figure 7 shows GAP/AP yield stress vs temperature, although over a more limited range of strain rates. As in Fig. 6, the curves are similar in shape at the different strain rates. Log-log plots of yield stress vs strain rate (similar to Fig. 5 but not shown) produced a family of curves with an inverse slope of approximately N =

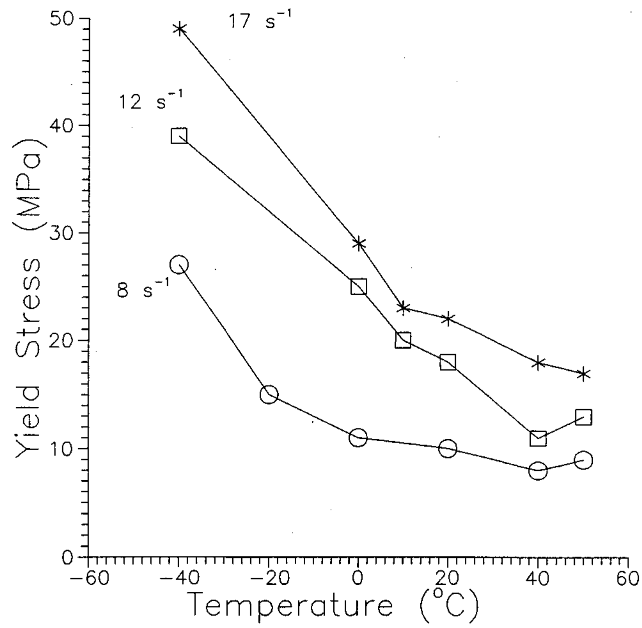

Fig. 7 Yield stress as a function of temperature for GAP/AP propellant over a limited strain rate range. The propellant curves have similar shapes relative to one another and a yield stress which varies linearly with strain rate; thus a modified strain rate exponent equation [Eq. (4)] can predict as in Fig. 5.[19]

0.38. When Eq. (3) is used to predict the yield stress at the higher strain rate from data at a lower strain rate (Fig. 7), the results [see Table 2, Eq. (3)] are not correct. Instead a modified version of Eq. (3) is used, based on Eq. (2) in which the yield stress varies as the logarithm of strain rate, so that the numerator is now a double logarithm:

$$N = [\Delta \log(\log \dot{\varepsilon})/\Delta \log \sigma_y]_{T,\varepsilon} \qquad (4)$$

The predictions [Table 2, Eq. (4)] are more accurate except at temperatures below T_g. Because these results are from a limited range of strain rates, however, the question arises as to whether this technique holds over a larger strain rate range for these softer materials. From Fig. 5, the JA2 propellant appears to have a relatively constant strain rate sensitivity over a broad range of strain rates (although with more scatter than steel). However, the results in Table 2 suggest that estimates of mechanical properties can be made at higher rates (or lower temperatures) from data at lower rates (or higher temperatures) as long as the material has not reached its glass transition temperature.

Newer Energetic Materials Testers

In recognition of the need for better characterization of energetic materials at different load application rates, several devices have been developed recently for evaluating dynamic mechanical properties in compression: the drop weight mechanical properties tester (DWMPT), the Ballistic Research Laboratory (BRL) servohydraulic test apparatus (MTS), and the Princeton Combustion Research Laboratory (PCRL) ballistic compressor (BC). The response of the energetic material is significantly different among these machines. Table 3 lists strain rate profiles and ranges, as well as stated temperature

Table 3 Comparison of small-scale mechanical properties testers

Name	Strain rate	Strain rate range,[a] s^{-1}	Conditional T range, °C
Drop weight mechanical properties tester[22]	Constant to yield, then variable	$1-10^3$	−40–64
Servohydraulic tester[18]	Constant	$1-10^3$	−40–50
Ballistic compressor[23]	Time varying	$1-6 \times 10^2$	−40–65
Split Hopkinson bar[21]	Variable	$1-10^3$	−40–50
Split Hopkinson bar[19]	Variable	$1-10^3$	−60–50

[a]Function of machine as well as sample size.

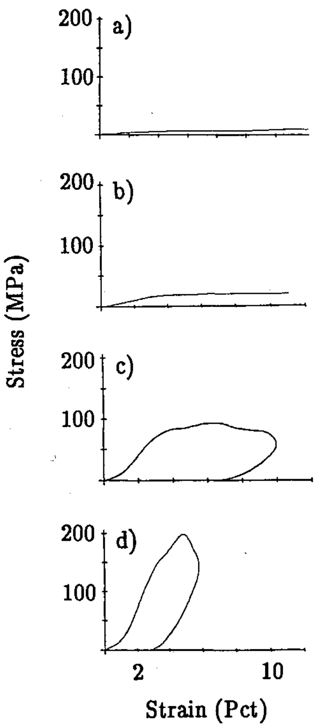

Fig. 8 Stress-strain curves for JA2 propellant in compression at ~250 s^{-1} from Lieb.[22] At higher temperatures a) 60°C and b) 20°C, ductile behavior occurs while at low temperatures, c) −20°C, and d) −40°C, brittle behavior is shown.

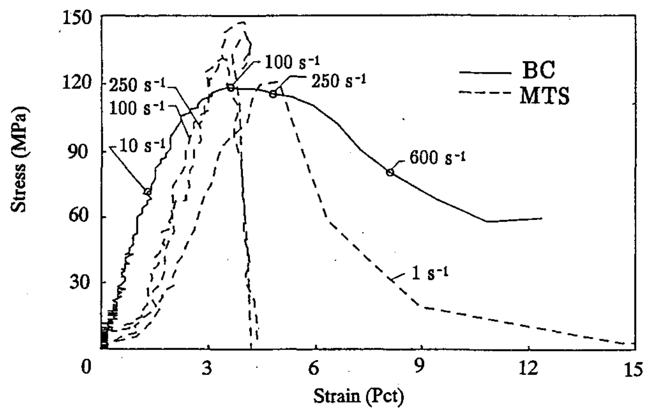

Fig. 9 Comparison of MTS and BC compressive stress-strain curves for HELP1 propellant at −40°C (after Messina et al.[23]). The dependence of material properties on strain rate is evident from the different curves.

ranges, for the devices to be discussed below. SHPB is included for completeness.

Drop Weight Mechanical Properties Tester

Lieb[22] is studying the high rate deformation response of several gun propellants with the drop weight mechanical properties tester. In this device, a falling weight imparts a force through a ram onto a sample. The compressive stress/strain curves at four temperatures for JA2 gun propellant (Fig. 8) show ductile response above 20°C (Figs. 8a and 8b) with yield and plastic flow of the material. At temperatures of −20°C or lower (Figs. 8b and 8c), varying degrees of brittle failure occur. The glass transition temperature of JA2 is approximately −20°C, so these results support the earlier discussion of transition temperature effects.

Ballistic Research Laboratory Servohydraulic Test Apparatus

Another device currently used for material testing at high strain rates is the BRL servohydraulic tester. Lieb et al.[18] test gun propellants over a range of temperatures at a strain rate of 100 s^{-1}. The conventional and failure parameters (Fig. 3) are reported for gun propellants (M14, JA2, M30A1, and XM43) at temperatures from −40 to 50°C and are consistent with the appearance of the tested materials observed after impact, supporting the different failure modes. In other experiments with Lu,[18] the response of these same uncased materials to shaped charge jet (SCJ) impact was evaluated. No direct correlation was found between the failure parameters and SCJ results. However, a strong correlation was discovered between changes in two closely related parameters: E_f and NFM, and the change in impulse response at lower temperatures. Lieb et al.[18] suggest this indicates that in the regime where mechanical response changes control the explosive response, a link may exist between the change in failure property measurements and the change in the impulse of the vulnerability response.

Princeton Combustion Research Laboratory Ballistic Compressor

Messina et al.[23] currently use a device called the ballistic compressor (BC) to obtain mechanical properties at high strain rates. Rapid gas compression imparts a ballistic-like pressure pulse on a piston located adjacent to a test sample. A mechanical properties test chamber is attached to the BC for obtaining load-displacement and pressure information. The main difference between the BC and the MTS is the first allows a time-varying strain rate in the sample, whereas the other subjects the sample to a constant strain rate (MTS). Thus, differing stress-strain curves are obtained for identical propellants, as shown in Fig. 9.

Several different variables have been studied with the BC including grain length to diameter ratio (L/D), perforations, propellant formulation, and testing temperature:

1) Messina et al.[23] found for JA2 propellant at 20°C, L/D has no effect on the material response in the elastic and initial plastic regions. However, fracture occurs more readily for an L/D = 1.6 with ductile failure for the same material with an L/D = 1.0.

2) HELP1 propellant samples with L/D = 1.6 were tested at −40°C with 0 and 19 perforations. Again the elastic and plastic regions of the stress-strain curves were similar, but fracture was significantly greater for grains with perforations than without.

3) The stress-strain curves for several different propellant formulations (M9, M30, and HELP1) were obtained at −40 and 65°C (see Fig. 10). It appears work hardening materials such as M9 can support significant loads before fracture and

Table 4 **Mechanical properties of JA2 propellant at 20°C obtained from four different mechanical properties test devices**

Device	Strain rate at yield, s^{-1}	Yield stress, MPa	Yield strain, %	Compressive modulus, MPa
MTS[18]	1	9.2	3.25	410
	100	14.5	3.06	770
	Average value[a]	22.5	2.91	670
BC[23]	27	15	2.82	590
DWMPT[22]	298	20.5	3.55	950
SHPB[21]	2,070 (L/D = 1)	29.7	1.67	2,250
	3,080 (L/D = 0.5)	32.4	2.26	1,710
	9,450 (L/D = 0.212)	50	7.11	835
	11,080 (L/D = 0.180)	47.5	4.25	1,290

[a]As reported in Lieb et al.[18] Unless shown, L/D = 1.

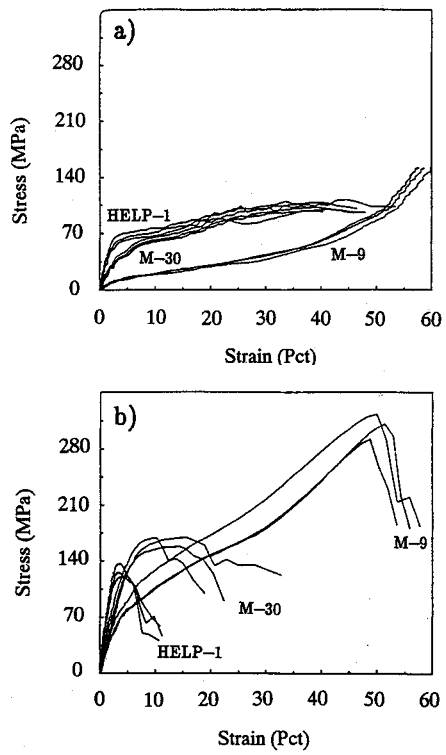

Fig. 10 Comparison of compressive stress-strain curves for three different propellants at a) 65°C and b) −40°C (after Messina et al.[23]). The behavior of all the propellants is more brittle at the lower temperatures.

can reach similar strains regardless of temperature, whereas work softening materials like M30 and HELP1 show strong fracture sensitivity to temperature. The yield properties of all three materials are strongly affected by temperature which correlates with the temperature shift discussion presented earlier.

Split Hopkinson Pressure Bar

BRL also uses a Hopkinson bar for testing energetic materials at high rates.[21] The same propellants were tested with the BRL SHPB as with the DWMPT. The material properties are evaluated using the terminology of Fig. 3. Strain rates from 1.1×10^3 to 10^4 s^{-1} were obtained in samples with L/D ratios from 1 to 0.18. The results show that the yield stress increases with increasing strain rate for M30 and JA2 propellants, but stays about the same for XM39. The initial moduli increase and yield strains decrease for all three propellants. These higher rate tests also produce more fracture in all samples than do the lower rate DWMPT tests. The L/D ratio has a pronounced effect on the results: for reduced L/D values, the yield stress increases, but the strain at yield and modulus both decrease which is opposite to the cases with L/D = 1. The explanation for this is flatter samples fail earlier in a shear mode which does not happen with the larger samples.[21] Currently, BRL is modifying the SHPB by adding a gas pressurization system which allows testing propellant at ambient pressures of up to 200 MPa. A complete description of the design is found in Hoffman.[24]

Comparison of Mechanical Property Data from the Four Testers

A comparison of mechanical properties (Table 4) for JA2 at 20°C from the test devices previously described illustrates that strain rate increases of four orders of magnitude result in nearly a sixfold increase in yield stress, and a doubling or tripling of modulus, while yield strain remains nearly constant. Similar tables can be created for other propellants than JA2. However, to obtain consistent mechanical property values for design purposes, finite element simulations, etc., the variation in properties observed in the SHPB results, attributed above to strain rate effects, should be separated from L/D effects.

Conclusions

The importance to hazards analysis of characterizing energetic materials response over as broad a range of strain rates as time and money permit has been demonstrated. Conventional Instron machines operating in a tensile mode have a limited strain rate testing range due to their crosshead speed. In the compressive mode, the strain rate range is further limited by the crossheads contacting one another. Although the range can be extended by using time/temperature shifting procedures, Instrons cannot effectively reach the typical IM strain rate levels shown in Fig. 11.

New test methods thus take on a greater significance for obtaining high-rate compressive mechanical properties. Based purely on strain rate capabilities, these devices allow for larger ranges to be tested (see Table 3). These ranges are effectively extended using temperature-shifted values as shown in Fig. 11. The abscissa now includes the shift factors (simply an approximation using the HTPB propellant data in Fig. 2) and illustrates how the low temperature capabilities of the devices (see Table 3) further extend their strain rate ranges, to approach and perhaps even surpass, the room temperature IM ranges. Linear increases in strain rate capability, therefore, are not as significant as exponential increases obtained from temperature reductions [see Eqs. (1–4)]. Although the WLF Eq. (1) may not be applicable to the much higher IM rates, researchers[16,17] have shown the applicability of time-temperature equivalence in compression at rates of up to 100 s^{-1} for gun propellants.

Other suggestions which might lead to improved characterization of energetic materials mechanical properties include: first, testing the material with both a time-varying and constant strain rate where possible to span the range of possible material response; and second, varying the sample size over as large a range as possible since the L/D ratio has been

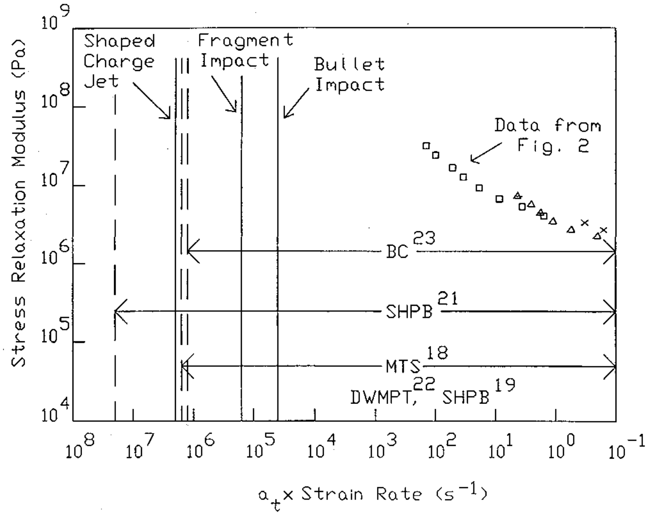

Fig. 11 Strain rate ranges of small-scale mechanical properties testers are extended further by testing at lower temperatures and then using a shifting technique. These extended ranges approach the IM test ranges.

shown to significantly affect the results of mechanical properties tests.[21,25] Most mechanical properties testers currently in use impart a uniaxial stress on the sample. Thus, tests are needed which subject the sample to a biaxial state of stress to simulate realistic hazard scenarios. Messina et al.[23] are modifying the ballistic compressor for such biaxial stress capabilities. Finally, statistically based experimental design techniques may be helpful due to the many uncontrollable variables in the average test. Gazonas[25] and Cost[26] provide examples of sound experimental design techniques applied to the testing of energetic materials.

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