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Mechanical Response Comparison of Gun Propellants Evaluated Under Equivalent Time-Temperature Conditions

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13. ABSTRACT *(Maximum 200 words)*

Compressive stress relaxation measurements have been performed for single- (M14), double- (JA2), and triple-base (M30) propellants, as well as a nitramine composite (M43) gun propellant. This was done to evaluate the response of gun propellants at higher rates than can be easily reached within the laboratory by calculating time-temperature shift factors from these relaxation curves. However, in order to apply these shift parameters to high rate events to predict propellant mechanical response and damage, a link must be established between predicted equivalent response and the actual mechanical and failure behavior observed for these propellants.

The mechanical response of these four propellants was characterized at strain rates, which spanned four orders of magnitude, and at the corresponding shifted temperatures. Test results show that the mechanical response for a given propellant type under each of these temperature-rate conditions was the same in the strain domain for which the relaxation shift factors were measured. In addition, the failure response for a given propellant type also proved to be nearly identical at strain levels outside the domain of the stress relaxation tests. These observations permit greater confidence to be placed in the prediction of mechanical and failure response for gun propellants undergoing deformation in strain rate regimes outside the current range of laboratory measurement.

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1. INTRODUCTION

The response of gun propellant to mechanical stress plays a critical role in the evolution of pressure during the ballistic cycle. Attempts to link the relationship between mechanical measurements performed in the lab and both gun performance and vulnerability have made considerable progress[1,2,3]. Recent work has revealed that at low temperatures, the change in magnitude of failure parameters measured on a single propellant grain correlated well with the change in magnitude of the explosive response of propellant beds upon impact with shaped charge jets[2,3]. However, the mechanical response measurements were performed at rates of about 100 s^{-1}, whereas the rate of mechanical deformation during the jet interaction is estimated to be between 10^5 and 10^6 s^{-1}. This observation led to studies, completed within the last year, in which compressive stress relaxation measurements[4] were performed and, time-temperature shift factors were employed to obtain master curves for the four basic propellant types. This information provides the temperature shift required to simulate the mechanical response characteristics of the propellant undergoing deformation at the corresponding higher strain rate.

There are, however, two questions that, if answered, would help establish much greater confidence in the shifted results. First is the behavior actually simulated when these shifts occur, and second, if the simulated behavior is represented, does the correspondence extend outside the strain level at which the relaxation measurements were made, that is, into the region of failure? In seeking answers to these questions, four series of tests were performed using the same propellant lots that were used to establish the relaxation curves. Each propellant response was characterized at conditions predicted by the shift factors to be equivalent. The mechanical responses were then compared to reveal what similarities and differences existed.

2. EXPERIMENTAL PROCEDURE

2.1 Establishment of Testing Conditions. The strain rates for the uniaxial compressive measurements were selected to be 100, 10, 1, and 0.1 s^{-1}. The temperatures corresponding to these rates were determined by the time-temperature shift factors measured earlier for each of the propellants and were selected so that each propellant would maintain the same mechanical response at each strain rate. Figure 1 shows the logarithm of the shift factors versus temperature taken from earlier work[4]. The stress relaxation curves used to generate the values of A(T) were not corrected for temperature. These uncorrected curves were used since the comparisons being made here are among tests performed at different temperatures. The corrections need to be applied when constructing master curves representing responses at the same temperature but at different rates. Testing conditions were determined from the curves in Figure 1 and are presented in Table 1.

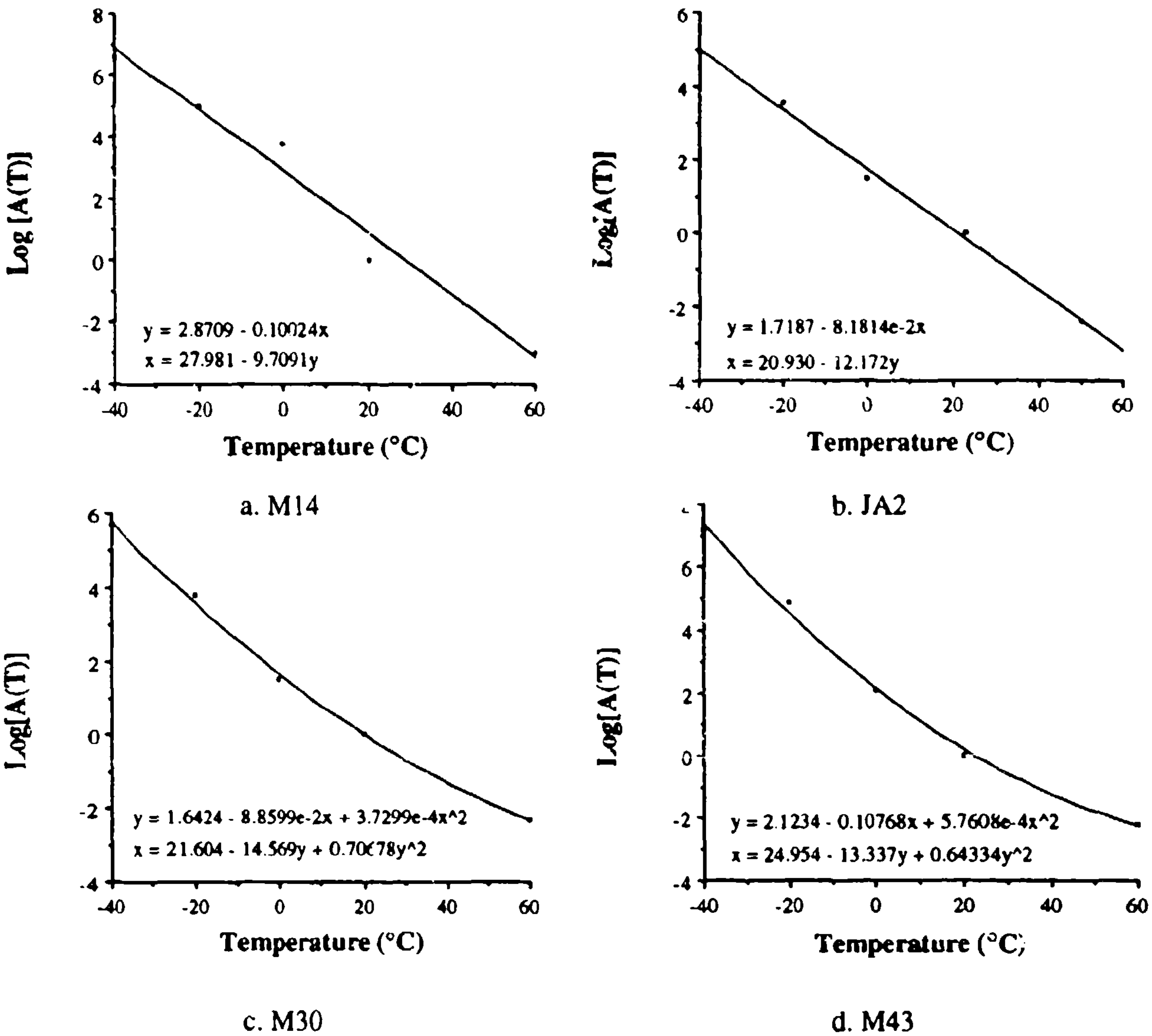


Figure 1. Log[A(T)] Versus Temperature Determined from Stress Relaxation Experiments [A(T) values are not temperature corrected]

2.2 Description of the Tester and Procedure. The propellant mechanical response was measured using a specially designed servohydraulic tester, illustrated in Figure 2. The machine allows compression measurements to be performed from quasistatic rates to rates as great as 10^3 s^{-1} for a specimen with a nominal length of 1 cm. Compression can be arrested at a predetermined strain by adjusting the anvil height and permitting contact between the impact bell and cone (which shunts the force around the specimen). Temperature conditioning was obtained within an environmental chamber surrounding the compression tool and was able to be controlled to within ±1°C. A complete description of the device is given in Reference 5.

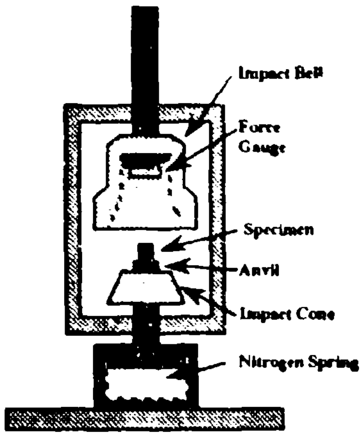


Figure 2. Servohydraulic Tester Schematic

Table 1. Equivalent Temperature Shifts from Strain Rate of 100 s^{-1}

Propellant	Strain Rates		
	10 s^{-1}	1 s^{-1}	0.1 s^{-1}
M14	-10°C	-20°C	-30°C
JA2	-12	-24	-37
M30A1	-14	-26	-37
M43	-13	-24	-34

Table 2. Nominal Percent Composition of Propellants

	M14	JA2	M30A1	M43
Nitrocellulose (NC)	89	59	27	4
NC Nitration Level	13.0	13.1	12.6	12.6
Nitroglycerin (NG)		15	23.4	
Nitroguanidine (NQ)			47.2	
DNT	8			
DBP	2			
DPA	1			
Ethyl Centralite (EC)			1.4	
Diethylene Glycol Dinitrate		25		
Akardit II		1		
K_2SO_4			1	
RDX (Ground)				76.0
Cellulose Acetate Butyrate				12.0
Plasticizer				8

The specimens were prepared from multiperforated gun propellant grains whose formulations are listed in Table 2. To make the sample suitable for stress and strain measurements, the grain ends were cut with a diamond saw so that they were flat, parallel, and perpendicular to the grain axis. The specimen-length-to-diameter ratio was made equal to 1 so that grains of different diameters have nearly the same end effects. Temperature conditioning was achieved by placing prepared grains inside the environmental chamber for a time at least twice that needed to reach thermal equilibrium (30 minutes in most cases). Testing of the specimens took place within the conditioning chamber, so no transfer was required, and therefore, no thermal disruption occurred.

The tests were conducted in accordance with a proposed NATO draft STANAG entitled "Uniaxial Compressive Test", which is an updated version of the test entitled "Uniaxial Compressive Gun Propellant Test" in CPIA Pub 21. Five specimens were tested at each temperature, and all reported results

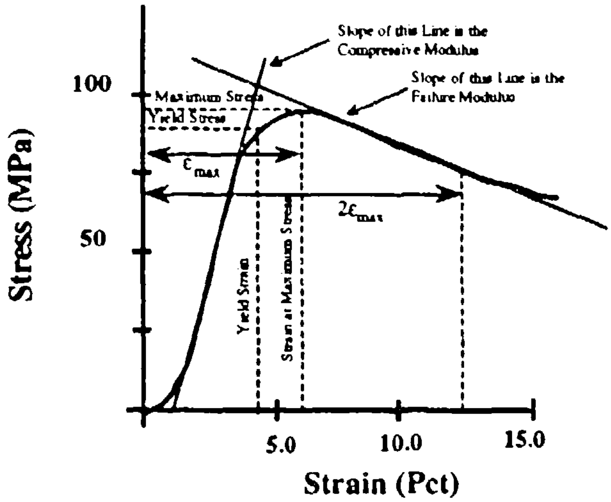


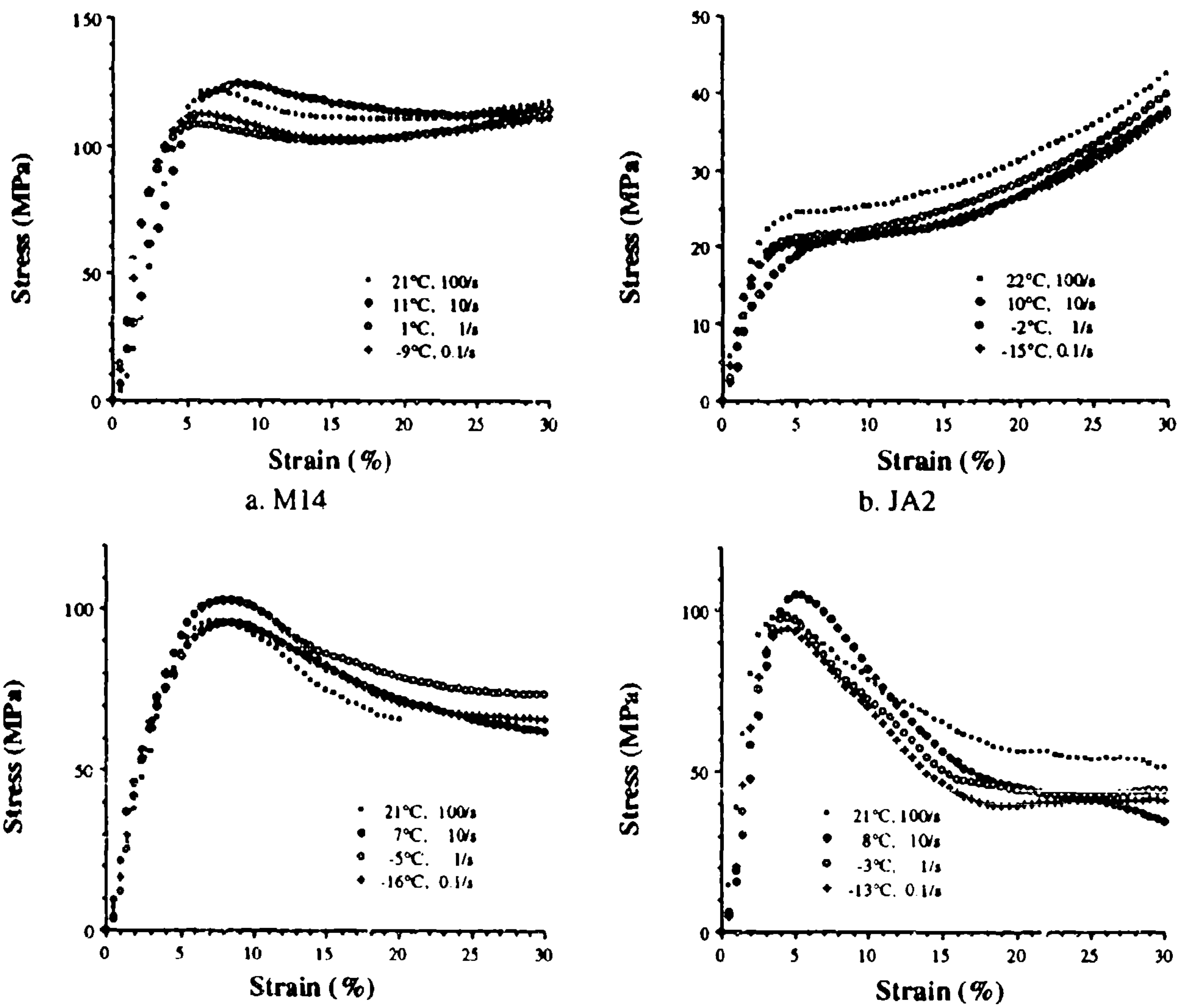
Figure 3. Stress-Strain Dia_ram Illustrating the Measured Parameters

are the average of the five data sets. The mechanical parameters, maximum stress, strain at maximum stress, yield stress and strain, modulus, and failure modulus, were recorded. A diagram illustrating these parameters is presented in Figure 3. Note that the failure modulus is defined as the slope of the stress-strain curve in the linear region between yield and twice the strain at maximum stress. If no maximum stress is observed in the vicinity of yield, as is sometimes the case with JA2 and other propellants with plastic responses, the slope is taken between yield and three times the yield strain.

3. RESULTS AND DISCUSSION

The mechanical response curves for each propellant are presented in Figure 4. Each curve in the plots corresponds to one of the four conditions predicted by the stress relaxation data to have an equivalent mechanical response, as outlined above.

To provide a basis for comparison, examples of the effects that strain rate and temperature have on the response of propellants are shown in Figure 5. The response of JA2 at constant temperature for various strain rates is shown in Figure 5a, and the response of M43 at constant strain rate for various temperatures · shown in Figure 5b. Note the changes in the level and form of response. For JA2, the form of the response remains about the same, while the stress levels show dramatic increases. This is a result of the viscoelastic-plastic response of JA2. Failure here is plastic with an increasing degree of work hardening with strain rate. For M43, both the level of the response and the form change with temperature. At high temperature, stress levels are lower and the response is more plastic. As the temperature decreases, the stress levels increase and the response becomes more brittle, as indicated by the more rapid decrease in stress level after maximum stress is reached. At the lowest temperature, the response has become very brittle with the highest stress levels attained, earlier failure strain realized, and a total loss of load bearing ability occurring after failure. Similar response changes have been observed for JA2 at temperatures below -20°C at rates of about 100 s^{-1}. The temperature at which this transition to brittle response occurs has been observed to depend on the strain rate.



a. M14 b. JA2

c. M30 d. M43

Figure 4. Mechanical Responses of Each Propellant at Equivalent Strain Rate and Temperature Combination

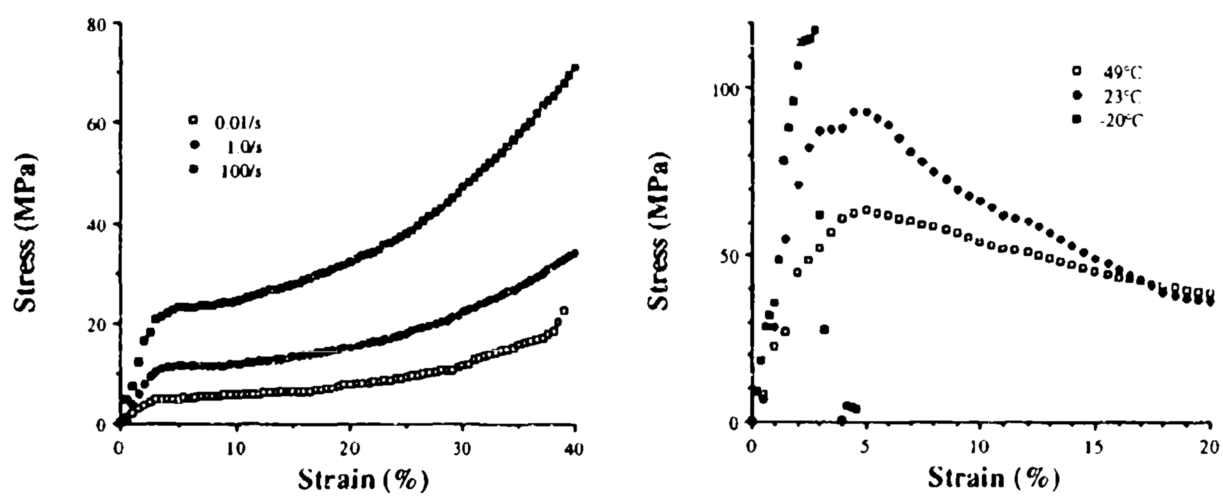
Listed in the top section of Table 3 are the mechanical response parameters derived from the curves in Figure 5. Note that for JA2, the yield stress increases by a factor of more than three, the modulus by a factor of more than four, and the failure modulus by a factor of more than five as the rate goes from 0.01 to 100 s^{-1}. These numbers reflect what is shown in the curves and indicate that the propellant is becoming stiffer and stronger with strain rate. For M43, the observed maximum stress, the yield stress, and modulus all decrease by about a factor of two, while the failure modulus shows dramatic change as the temperature goes from -20°C to 49°C. These numbers indicate the change from very brittle behavior to more plastic response, and again reflect the form of the curves presented in the figure. These plots and the associated numbers show that characteristic response changes are significant wit anges in either strain rate or temperature and that these changes can be demonstrated with stress-strain curves and their derived parameters.

Using the above as a preface for comparing the results shown in Figure 4, it can be stated that the form and stress level of each set of curves were very much the same for a given propellant type. This observation is further supported when the parameters derived from those curves (shown in Table 3) are compared. Again, for each propellant, no significant change or difference was observed. The similar modulus values indicated that the mechanical responses in the strain region where the stress relaxation measurements were taken, between 2% and 5%, were the same. In addition, it was also shown that the equivalent response extends outside this strain region into the region of failure. Maximum stress and strain values were the same, as were the yield stress and strain values. The equivalent response has been shown to extend significantly into the region of failure. Note that failure modulus values, which measure the change in load-bearing capability of the material after yield, were the same for each propellant. These results strongly indicated that the temperature-rate equivalence determined by stress relaxation data predicted the mechanical response and failure mode at each corresponding temperature and rate.

One set of results appears to be out of line with these observations. The test conditions at the strain rate of 10 s^{-1} proved to provide the mechanical impedance match between the machine and specimen, which caused problems in maintaining constant strain rate during the deformation of the specimen. At higher rates (100 s^{-1}), the kinetic energy of the actuator was sufficient to maintain a constant rate. At lower rates (1 and 0.1 s^{-1}), the rate was low enough so that the pressure regulation within the actuator of the tester matched the stress changes in the specimen. At 10 s^{-1}, however, stress changes were rapid enough and kinetic energy values were low enough to cause nonuniform strain rates in the early portion of the deformation. Adjustments were performed to minimize the nonuniformity, but some variation of the strain rate still occurred within the first 2% to 3% of deformation. The result, since the material is rate sensitive, was a systematically lower modulus and corresponding higher strain values for results at 10 s^{-1}. Note that the maximum and yield stresses, and the failure modulus values were more in line with the other values because of the strain rate reaching proper levels at higher strain. Several sets of data were taken at 10 s^{-1} with procedure modifications to minimize the strain rate variation. From the results of these several data sets, it is believed that if the strain rates had remained constant during the entire grain deformation, then the curves and the associated parameters would have fallen into more exact agreement with the results from other rates.

Table 3. Mechanical Response Parameters

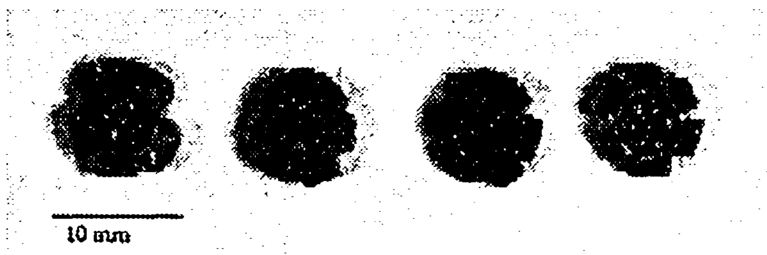
Propellant	Temperature (°C)	Strain Rate Rate (s^{-1})	Maximum Stress (MPa)	Strain at Max Stress (%)	Yield Stress (MPa)	Yield Strain (%)	Modulus (GPa)	Failure Modulus (GPa)
JA2	23	0.01	-	-	4.49	1.9	0.19	0.012
	23	1.0	-	-	10.0	2.7	0.41	0.034
	23	100	-	-	18.3	2.6	0.83	0.067
M43	-20	100	121.0	2.9	110	2.0	5.76	-31.7
	23	100	93.5	4.1	87.0	2.6	4.40	-0.61
	49	100	64.0	4.0	60.2	2.4	2.61	-0.20
M14	21	100	122.2	7.0	115.0	5.0	3.10	-0.21
	11	10	124.4	8.5	112.2	5.6	2.30	-0.12
	1	1	108.3	6.0	98.5	3.5	3.13	-0.10
	-9	0.1	112.6	6.0	102.0	3.6	3.34	-0.16
JA2	22	100	-	-	21.2	2.7	0.82	0.021
	10	10	-	-	15.7	3.2	0.63	0.029
	-2	1	-	-	18.5	2.8	0.72	0.023
	-15	0.1	-	-	17.6	2.5	0.76	0.022
M30A1	21	100	96.5	7.5	92.2	5.7	1.88	-0.34
	7	10	95.8	8.0	90.1	5.8	1.61	-0.24
	-5	1	103.0	8.0	93.1	5.2	2.41	-0.30
	-16	0.1	102.8	8.0	94.2	5.3	2.33	-0.36
M43	21	100	99.7	4.1	93.9	2.7	4.40	-0.41
	8	10	105.1	5.0	102.2	4.2	3.23	-0.59
	-3	1	98.4	4.4	88.7	3.3	3.60	-0.52
	-13	0.1	94.3	4.4	88.4	3.1	3.83	-0.49



a. JA2 at Constant Temperature

b. M43 at Constant Strain Rate

Figure 5. Mechanical Response Differences for JA2 as a Function of Strain Rate and M43 as a Function of Temperature



a. M14

b. M30A1

Figure 6. The Appearance of Tested Specimens from Each Test Condition

In Figure 6, the physical appearance of tested M14 and M30A1 specimens is presented. The indication is that the mechanical damage suffered by each propellant type is nearly the same. These grains suffered a combination of plastic failure and lateral fracture. (Note that the lateral fracture begins adjacent to the grain perforations.) The physical appearance among each of the other propellant types was also the same. All the JA2 specimens remained intact without any fracture. The M43 specimens fractured into many chards, with each specimen having about the same size distribution of chards. The condition of these specimens reinforces the conclusions drawn above.

4. CONCLUSIONS

The temperature and rate equivalence for mechanical response in gun propellants as determined by compressive stress relaxation procedures has been demonstrated. Mechanical response measurements were performed on the four basic gun propellant types (single-, double-, and triple-base, and a nitramine composite) at four different strain rates (100 s^{-1} to 0.01 s^{-1}) and at the corresponding temperatures that were predicted to provide equivalent mechanical response. In each case, the mechanical response of the propellant type remained nearly identical. This was true for the response measured in the strain region where the relaxation measurements were performed, and more importantly, this equivalent response was found to extend into the regions of strain corresponding to failure. For each propellant, very similar values for maximum stress, strain at maximum stress, yield stress and strain, compressive modulus, and failure modulus were observed among each propellant tested under equivalent conditions. These values of these parameters for the different curves were within the scatter found for specimens tested under identical conditions. The plots of stress versus strain characterized the response as virtually identical.

These results provide great confidence in the ability to predict mechanical and failure response of materials at rates outside those available within the laboratory by employing time-temperature equivalence.

5. FUTURE EFFORTS

In earlier studies[2,3], a strong correlation was discovered between the change in the mechanical failure response of the propellants studied in this report and the vulnerability response change that was measured when a bed of these same propellants was subjected to hypervelocity impact by a shaped charge jet (SCJ). Each propellant tested in those reports showed a similar trend between the failure parameter and impulse measurement, which indicated a SCJ response dependence on the mechanical failure mechanisms. However, there was no direct correlation between the values of the failure parameters and the impulse results among the propellants. One possible reason for not being able to discover a direct correlation could be the rate differences experienced by the propellants in the mechanical properties and the hypervelocity impact procedures.

It is estimated that the rate of deformation of the propellant while being deformed by the jet is between 10^5 and 10^6 s^{-1}. The mechanical response measurements typically are performed at 100 s^{-1}. The rate difference between the two processes corresponds to a factor between 10^3 and 10^4. With the information generated in earlier stress relaxation experiments and the demonstration of actual equivalent responses shown here, each propellant could be tested at a temperature appropriately lowered to see if the mechanical response tracks more closely to the vulnerability response. This will require tests at temperatures near -70°C, which will present new problems. However, if successful, the role that mechanical response plays in the area of vulnerability response should be made more clear. Tests are now scheduled for these propellants and will be reported.

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