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Analysis of Mechanical Properties for AP/HTPB Solid Propellant under Different Loading Conditions

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Abstract**—**To investigate the characterization of the mechanical properties of composite solid propellant (CSP) based on hydroxyl-terminated polybutadiene (HTPB) at different temperatures and strain rates, uniaxial tensile tests were conducted over a range of temperatures -60 °C to +76 °C and strain rates 0.000164 to 0.328084 s^{-1} using a conventional universal testing machine. From the experimental data, it can be noted that the mechanical properties of AP/HTPB propellant are mainly dependent on the applied strain rate and the temperature condition. The stress-strain responses exhibited an initial yielding followed by the viscoelastic phase, which was strongly affected by the strain rate and temperature. It was found that the mechanical properties increased with both increasing strain rate and decreasing temperature. Based on the experimental tests, the master curves of the tensile properties are drawn using predetermined shift factor and the results were discussed. This work is a first step in preliminary investigation the nonlinear viscoelasticity behavior of CSP.

Keywords**—**AP/HTPB composite solid propellant, mechanical behavior, nonlinear viscoelastic, tensile test, master curves.

I. Introduction

THE structural reliability of a solid rocket motor (SRM), which serves as the propulsion system and the key component of a tactical missile, is extraordinarily important. The performance of the SRM is influenced largely by the mechanical properties of propellant grain, this is because solid propellant is viscoelastic in nature and its mechanical properties and fracture mechanisms are highly dependent on temperature and strain-rate.

In general, for elastic and isotropic materials, it is assumed that the intensities of all mechanical properties are approximately constant, in the field of small deformations, in all ambient conditions or in the whole temperature range of use, as well as in all directions. The relationship between stress and strain is proportional and linear. But, highly filled elastomer such as solid propellant is considered as cross-linked polymers filled with solid particles, which show nonlinear viscoelastic behavior under various loading and pressurizing conditions or dewetting between polymer binder and particles. These materials exhibit very strong relationship between stress and strain depending on time and temperature. Therefore, to ensure the structural reliability of SRM for the tactical missile during different loading conditions, it is very important to know the mechanical properties and the fracture mechanisms of solid propellant.

In recent years, the mechanical properties of solid propellants have been studied by numerous researchers because of their extensive use and specific engineering requirements. Schapery's group focused on developing the solid propellant nonlinear viscoelastic and viscoplastic constitutive equations that account for stress rate, internal state variables, temperature, and growing damage, and the developed constitutive equations have been widely used in finite element models [1]-[4]. Özüpek compared several models and developed a constitutive model that gave the best representation of uniaxial tensile experimental data at room temperature under quasi-static loading [5]. Jung studied CSPs and developed a damage constitutive model based on elastic dewetting criteria and the softening effect to describe the nonlinear viscoelastic behavior obtained during stress relaxation tests in a temperature range of −90 °C to +60 °C [6]. This model was later extended to three-dimensional cases, and implemented in finite element analysis [7]. Chyuan numerically analyzed the structural integrity of HTPB propellant grains subjected to temperature loading [8], ignition pressurization loading [9], and Poisson's ratio variation under ignition pressure loading [10], using a constitutive model based on the static relaxation testing that employed the time-temperature superposition principle (TTSP) and reduced integration. Some recent studies have focused on the multi-scale constitutive behavior of solid propellants and studied the effect of micro-structural damage evolution, such as the nucleation and propagation of damage along the particle-matrix interface [11], and continuous void formation and growth [12], which was verified by uniaxial tension tests under low strain rates. Neviere generated the master curves of non-linear viscoelastic solids using TTSP of dynamic mechanical analysis and tensile tests conducted in the temperature range of −60 °C to +60 °C to describe the nonlinear viscoelastic behavior of HTPB [13].

In this paper, the uniaxial tensile tests are performed under various temperatures and strain rates (R) to get the mechanical properties of solid propellant. The main purpose of complete mechanical characterization of CSP is to determine the characteristic master curves for the mechanical properties. From the experimental tests, and based on the properties, the master curves of maximum stress (σ_m), strain at maximum stress (ε_m), and Young's modulus (E) are plotted by using predetermined time-temperature shift factor (a_T). All these three properties in logarithmic scale, normalized by factor

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($\frac{T_o}{T}$), are plotted versus reduced time (ξ), which is the reciprocal of the strain rate, corrected by the time-temperature shift factor as shown in:

$$\xi = \log(\frac{1}{Ra_T})$$

II. Experimental Methodology

A. Material and Specimens Preparation

The solid propellant used in this work is heterogeneous CSP which consists of solid oxidizer particles ammonium perchlorate (AP) 67%, and metallic fuel particle aluminum powder (AL) 18%, dispersing in polymeric binder matrix (HTPB) forming the rest percentage. These gradients are mixing at a certain time and temperature, and then the viscous mixture is cast in special molds with internal dimensions of 200×150×150 mm. Then the molds are placed in a large curing oven with temperature controlled at 60 °C, for a total curing time of 240 hours. After curing the molds are cut into sheets with a uniform thickness. Then the test specimens are produced using special cut press according to Joint Army-Navy-NASA-Air Force Propulsion Committee (JANNAF) standard, and the dimensions of the test specimens are illustrated in Fig. 1 [14].

Note that, the actual thickness of the specimens is 11.04 mm less than the standard one due to some limitation of the sheet cutting machine. As a quality control step, the produced specimens are checked by a non-destructive method for voids like air bubbles or micro cracks by X-Ray to ensure the result of experimental data. After that, the accepted specimens were stored in desiccators at ambient temperature and relative humidity RH ≤ 30% [15].

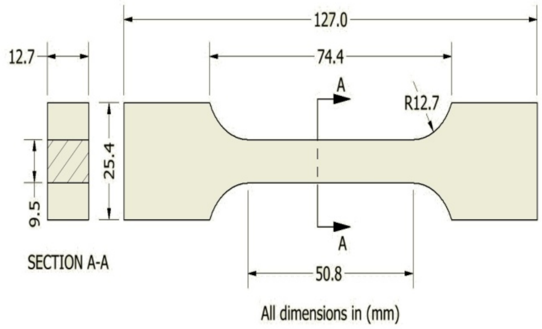

Fig. 1 Standard dimensions of the specimen [14]

B. Uniaxial Tensile Tests

Uniaxial tensile tests were conducted at various strain rates and different temperatures until the specimen was fractured by using a computer controlled universal test machine Zwick Z050. This machine has remote control software which could acquire, record, analyze, store, and print test data with minimum manual effort. The maximum permissible test load is 50 KN, and the range of crosshead speed varies from 0.0005 to 1000 mm/min with accuracy 0.004% of the set speed. The dimensions of the specimen such as thickness and width were measured in its gauge length region accurately before the test. The effective gauge length of the specimen is L_o=50.8 mm and the actual cross section area is A=104.88 mm^2. The specimens were pre-conditioned at least for three hours in an external conditioning chamber at the desired temperature to ensure the thermal equilibrium before the test.

Fig. 2 shows the results of the tensile test at different strain rates and at constant temperature (20 °C). The usual test crosshead speed is 50 mm/min; also we use 0.5 mm/min and 5 mm/min for slow strain rate response measurements, and 150 mm/min, 300 mm/min, 500 mm/min, and 1000 mm/min for high strain rate response.

Fig. 3 shows the stress-strain curves at constant crosshead speed (50 mm/min) and different temperatures ranging from the free strain temperature ($T_f \approx$ 70 °C) down to the glass transition temperature ($Tg \approx$ -50 °C) to show the effect of temperature in the behavior of the material.

Note that every experimental test was carried out on three specimens and the mean value of these three results is used for the analysis, also, before the experimental tests the specimens are conditioned in an external environment chamber for three hours to ensure the thermal equilibrium, and also the uniaxial tensile tests were conducted in an environmental temperature controlled chamber with tolerance ±0.1 °C.

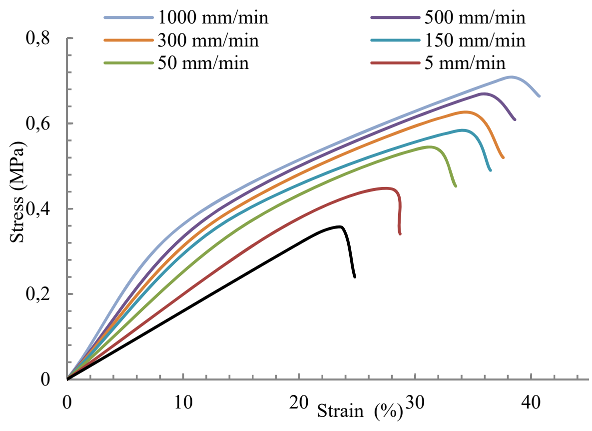

Fig. 2 Effect of strain rate on stress-strain curves [16]

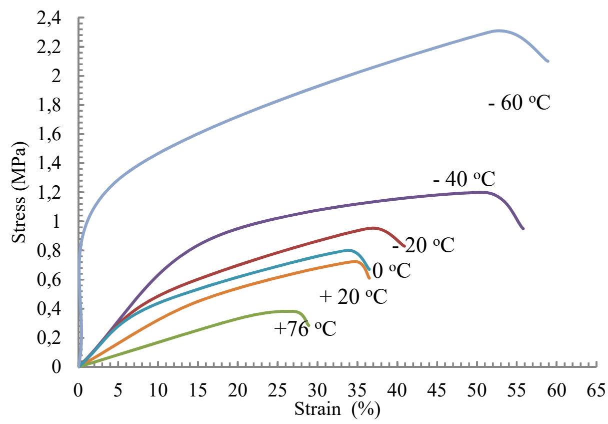

Fig. 3 Effect of temperature on stress-strain curves

III. Results and Analysis

A. Analysis of the Experimental Results

CSPs consist of different components with different Young's modulus, for example the Young's modulus of the oxidizers and the fuel particles are usually much greater than the Young's modulus of the binder. Therefore, when the propellant specimen is strained, the tension is mainly formed in the binder, while the solid particles can be roughly considered as nondeformable. Due to the deformation of the binder filling the space between the particles, stresses arise on the contact boundary between the particles and the binder. In general, during the tensile test, there is a failure of the bonding between some fillers and the binder, failure of the binder close to a solid particle. Vacuum holes are created, and their size increases with the stress/strain increase. When these vacuum holes reach a significant size (several micrometers) they cause micro failures initiating small cracks in the binder, and causing failure of the specimen. From Figs. 2, 3, it can be noted that the material has viscoelastic behavior because the strain rate or the rate of loading modifying the response of the material, while in the elastic material the strain rate plays no role.

The viscoelastic effects in solid propellant arise from the binder, as a viscous material, and from the friction between particles and binder during the debonding process. The non-linear behavior is related to the dewetting process which is also known to be time-temperature dependent. Also, it can be shown that at small strain rates (0.5-5 mm/min) the material behaves in a linear viscoelastic manner where the solid particles effectively reinforce the binder [17], but at high strain rates (150-300 – 500-1000 mm/min) the bond between the oxidizer and binder breaks down and effectiveness of the reinforcement is reduced so the material behaves in nonlinear viscoelastic behavior.

The mechanical behavior of propellants may be altered at low temperatures because of structural changes in the binder. An important modification of the mobility of the polymeric chain occurs when the temperature decreases and goes through a phase called (glass transition). The physical and mechanical properties of the polymer are greatly modified, when the temperature decreases the elastic modulus in particular increases significantly. But it can be noted that at high temperature the crosslinking chains between the polymers going to break, which result in decreases in elastic modulus and the capability of elongation at a certain level of stress becomes too high. In other words, at constant crosshead speed, the increase in temperature tends to decrease in Young's modulus, decreasing in maximum strain, decreasing in maximum stress. Figs. 4-6 show the dependence of the mechanical properties of CSP on the strain rate and temperature. In order to obtain these curves, at each individual temperature in the range between –60 and 76 ^{o}C, the CSP propellant specimens were tested in three different constant rate modes.

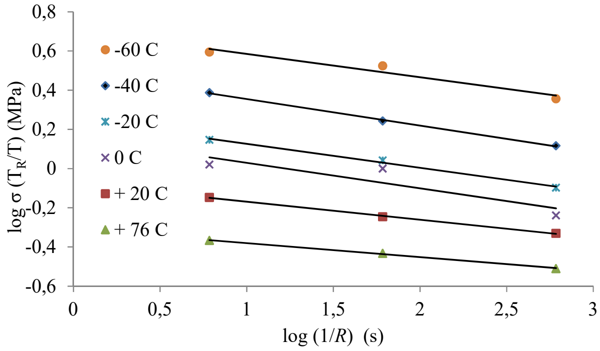

Fig. 4 Strain rate dependence of max stress for HTPB propellant at a series of different temperatures

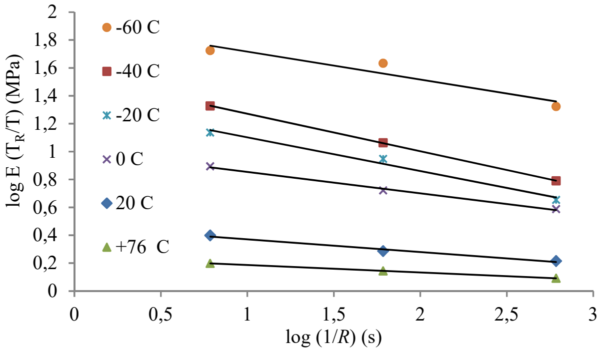

Fig. 5 Strain rate dependence of modulus for HTPB propellant at a series of different temperatures

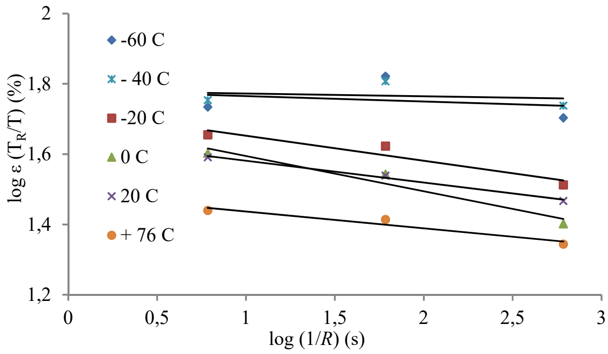

Fig. 6 Strain rate dependence of maximum strain for HTPB propellant at a series of different temperatures

B. The Master Curves of the Tensile Proprieties

The master curve of solid propellant based on reference temperatures is shown as the relationship between the mechanical property and the reduced loading time. The master curve is used mainly to predict solid propellant properties at various temperatures, according to TTSP and measurements at multiple test temperature conditions as a function of either loading time. From the master curve, polymer properties and behavior can be predicted or interpolated at different temperatures and loading from the test results.

The tensile properties are horizontally shifted using the shift factors which were obtained earlier in a previous work [15] according to WLF method based on reference temperature $T_R = 20$ °C, as shown in Fig 7. The time – temperature shift is one of the most important values in the structural analysis of viscoelastic materials because it allows the temperature impact to be converted to the time influence, which makes the analysis much easier.

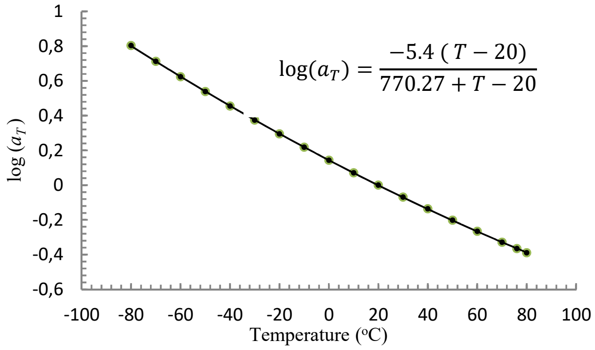

Fig. 7 Shift factors corresponding to each temperature

The master curves of the maximum stress, Young's modulus, and strain at maximum stress are plotted in Figs. 8, 9 and 10, respectively. The mechanical tensile properties of CSP gradually decrease as temperature increases. This result shows that there is a relationship between stress and time-temperature dependence.

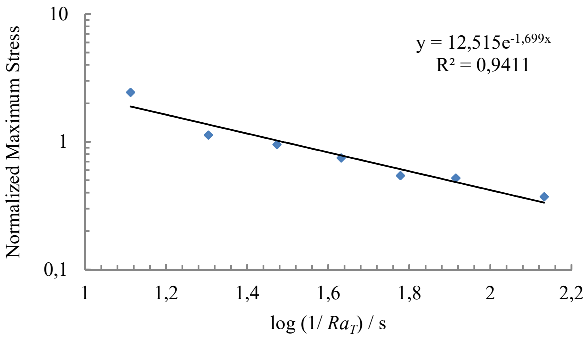

Fig. 8 Maximum stress master curve for HTPB solid propellant

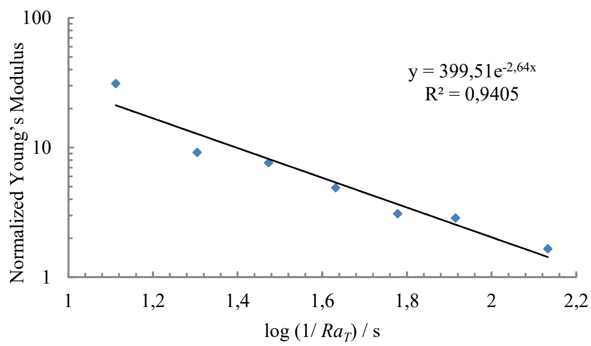

Fig. 9 Young's modulus master curve for HTPB solid propellant

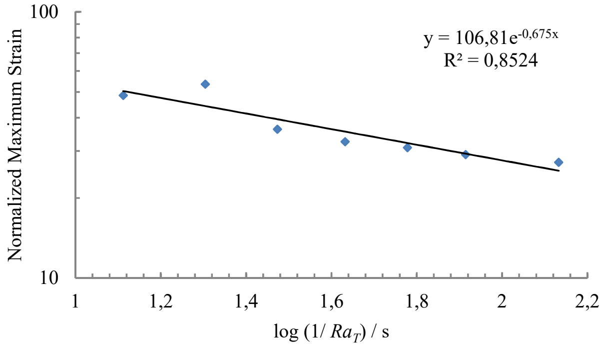

Fig. 10 Maximum strain master curve for HTPB solid propellant

IV. Conclusion

This paper discusses how to obtain the basic mechanical properties of solid propellant and how to convert these properties to obtain the master curves of the selected formulated by using the shift factors. The mechanical characteristics of the propellant are not obtained as straightforward as those for steel or other material since the propellant is non-linear viscoelastic material, so both temperature and strain rate must be taken into consideration. It is shown that a viscoelastic material may have extremely different mechanical properties depending on the type of load that act onto the viscoelastic body. Since the propellant being time and temperature dependent, they have a different mechanical behavior when changing the temperature and strain rate. From the experimental results, it can be noted that, Young`s modulus, maximum stress, and strain at maximum stress increase proportionally as the strain rate increases. In general, for a solid propellant, decreasing temperature has the same effect behavior of increasing the strain rate. Both the break strain and strain at maximum stress follow a non-monotonic behavior.

On the basis of uniaxial mechanical characterization of viscoelastic CSP, which have been made over the wide range of different modes of uniaxial tensile tests, the master curves were obtained that represent the mechanical properties dependence on temperature and strain rate. The master curves of stress, Young's modulus, and strain were plotted using the shift factors. The strain at maximum stress exhibits a nonlinear response which is related to diet and voids.

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