MEASUREMENT OF NONLINEAR EFFECTS IN CRACKED PARTICULATE COMPOSITES

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ABSTRACT

A series of experiments concerning loading rate and temperature effects were conducted on both uncracked and edge-cracked "biaxial" specimens made of a specific particulate composite. By using two loading rates and three temperatures, the material's global response and local near-tip deformation were obtained. The crack propagation process and velocity were also studied by the photographs taken during the tests. Furthermore, the displacement singularity order due to the presence of the crack was evaluated at various stages of crack propagation according to continuum theory. Finally, the geometric effect was studied by using specimens with two thicknesses.

From the non-linear biaxial stress-strain curves of the cracked specimens, it is noted that the temperature effect is more profound in altering the material's mechanical response compared with the loading rate within the ranges studied. Crack propagation was also found to be a highly nonlinear blunt-growth-blunt-growth process, and the displacement singularity was found to be consistent with Benthem's analytical result for sharp crack tips, while certain corrections were needed to account for the crack blunting.

INTRODUCTION

Solid rocket propellant, a mixture of metal powder, finely ground crystalline particles and polymeric binder (1), serves not only as the fuel for the propulsion system, but also a structural component of the entire rocket. Numerous defects and cracks have been found inside the real propellant grains due to manufacturing, transportation, storage and assembly processes, and these cracks could increase the burning surface area, change the thrust-time profile, or even lead to the catastrophic failure of the whole structure. Meanwhile, because of the inclusion of the elastomeric binder, the propellant material exhibits strong time-temperature-dependent characteristics (2). A better understanding of propellants' failure mechanism, especially under different environmental conditions, is believed to be beneficial to the safety control and life prediction of the whole rocket.

Over the years, the senior author and his colleagues have been working intensively on characterizing the failure mechanism of inert propellant (3-6). The present research is intended to extend the previous work by using two loading rates, 2.54mm/min and 25.4mm/min, and three temperatures, -65°F, 72°F and 165°F, so as to assess the material's time-temperature dependency under typical storage conditions.

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TEST SPECIMENS AND EXPERIMENTAL PROCEDURES

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To simulate the stress conditions frequently occurring in the real propellant grain, a "biaxial" uncracked specimen (figure 1 (a)) was used in the stress relaxation test, where a 3% initial strain was applied at each temperature with a loading rate of 127mm/min. The grooves cut at both sides of the strip were designed to prevent premature failure near the bonding area. Meanwhile, specimens with the same geometry were also employed in a series of tension tests to quantify the material's stress-strain relationship at various temperatures. Finally, an edge-cracked specimen (figure 1 (b)) was tested over the mil-spec temperature range (-65°F to 165°F) with the two loading rates.

Every specimen was machined into the designed shape before it was glued to the aluminum grips by a special epoxy adhesive. A 25.4mm long starter crack was made prior to the experiment and a 5 line/mm cross grid was selected to have the ability of identifying the roles of the big crystalline particles (≈0.3mm in the largest dimension) and suppressing the fine ones to display the global response at the same time. Detailed information on how to apply this cross grid can be found in Ref. (7). Specimens with two thicknesses, 2.54mm and 12.7mm, were used in the experiments, although the thicker ones were only tested at the room and elevated temperatures so far. It is expected to evaluate the geometric influence on the material's mechanical behavior by comparing these two groups of tests.

Except for the room temperature tests, a thermally-controlled cabinet was used to either heat up or cool down the test samples. After the desired temperature was reached, the specimen was soaked for sufficient time depending on its thickness so that the temperature gradient was avoided across its whole body. For cracked specimens, photographs were taken at predetermined intervals during the experiment to record the deformation of the applied grid. Background lighting was crucial in the picture-taking process and a fiber optic illumination ring was used to provide a uniform light intensity on the surface of the specimen. The recorded pictures were digitized to generate the data files of the deformed patterns which were used to calculate the displacement and strain fields.

RESULTS AND ANALYSIS

Since only the thin specimens were tested over the mil-spec temperature range, relaxation analysis did not include the thick specimen data. In the experiments, the gradually decreasing load required to maintain the 3% global strain initially applied to the specimen was recorded from 3 seconds to 1 hour after reaching 3% strain. The relaxation modulus at every temperature could then be evaluated by the varying load at the constant global strain (figure 2):

$$E_r(t)=\frac{\sigma_r(t)}{\varepsilon_0} \qquad (1)$$

where $\sigma_r(t)$ is equal to the ratio of the varying load to the average specimen cross-section area and ε_0 is the 3% global strain..

By adopting the following relationship to formulate the variation of the relaxation modulus, E_r, with respect to the time, t:

$$E_r(t)=E_0+E_1t^{-n} \qquad (2)$$

(where $E_0=0.98\text{N/mm}^2$ and $n=0.32$ within the test temperature range) and applying the time-temperature superposition principle, one could generate the master curve for relaxation modulus at room temperature (figure 3). It is seen that, from the master curve, the simulated propellant material shows a strong viscoelastic nature and the mil-spec temperature range covers the transition of the material's mechanical response from brittle to ductile.

From the nonlinear stress-strain curves obtained during the tension tests, the low temperature shows a significant effect by drastically increasing the maximum stress, while the global strain in this case is the smallest by comparing the three tests (figure 4). This observation verifies the argument that the low temperature strongly pushes the material to the brittle side, while, at the room and elevated temperatures, the simulated propellant behaves closer to the rubbery state with less difference compared with its low temperature behavior.

As far as the cracked specimens are concerned, the crack propagation shows a blunt-growth-blunt-growth process which is highly nonlinear. Although the amount of blunting was slightly smaller for the low temperature test, its presence was obvious. The blunting came after the crack opening and was generated by the stretch of the fiber bundles in the near-tip region. The blunting effect slowed down the crack growth velocity and the breakthrough of the resin-rich zone in front of the blunted crack tip induced further crack extension. Figure 5 shows the crack growth for the thin specimen under every test environment, and it is noticed that the crack grew much faster at the low temperature, while the difference between the room and elevated temperature test data was quite small. Furthermore, the loading rate effect appears to be negligible for the room and elevated temperature crack propagation, but it becomes more influential at the low temperature. Meanwhile, the load versus global extension curves (figure 6) also highlight the large increase in the maximum load and lower global strain at fracture due to low temperature, which physically reflects the change of the solid propellant's mechanical characteristics. Again, although the loading rate seems to raise the maximum load to some extent, its effect is smaller compared with the temperature. If the thickness effect is included, one can generate the curves of load/thickness versus the global strain for both the thin and thick specimens under two loading rates at the room and elevated temperatures (figures 7 and 8). These curves illustrate a nonlinear decrease in load/thickness when the specimen gets thicker and the thickness effect seems to be more profound than the loading rate in altering the variation of the load/thickness. Meanwhile, the lower loading rate might be more sensitive to the variation of specimen thickness, although it is not very significant within the range tested

From the pictures taken during the experiment, local crack opening, blunting and resharpening process (figure 9) is clearly revealed and this crack propagation pattern bears only a quantitative (not qualitative) difference for every temperature and loading rate. In the crack growth process, failure usually occurs at the interface between the particle and matrix which can be seen on an SEM picture (figure 10), and this propagation mechanism results in a locally undulating path skirting around the filler particles. The vertical displacement contour (figure 11 (a)) obtained from digitizing the cross grid patterns shows an almost rigid body displacement field above and below the crack surface due to crack opening and blunting, while a displacement gradient is noticed in front of the crack tip. An intense strain zone (figure 11 (b)) which is related to the material's dewetting mechanism is also observed close the crack tip and its size enlarges with the increasing global strain. Although crack opening induces large shear strain in the near-tip region (figure 11 (c)), it appears to be a local behavior and the large portion in front of the crack tip remains to be purely stretched without shearing.

Displacement data measured along the vertical line passing through the crack tip were used to estimate the displacement singularity order where the cracks intersect the free surface according to the algorithms explained in the appendix. Different from what was reported earlier (8) on a poorly graded inert propellant, the current test specimens seem to be better characterized by the continuum theory since the previously observed micro-cracking rarely occurs in this case, especially outside the intense strain zone. Although the average value of the displacement singularity for sharp crack tips, λ_u=0.70, at various temperatures, head rates, and global strain, agrees reasonably well with Benthem's analytical result, λ_u=0.67 (9) for incompressible materials, the result for blunted cracks shows a slightly higher value of 0.85 indicating a less severe stress intensity.

CONCLUSION

It is noted that, for both uncracked and cracked specimens, the low temperature significantly increases the material's strength and decreases its ductility, while the material's mechanical response and failure mechanism at the elevated temperature seem to be quite similar to those at room temperature. The loading rate might be more influential at the low temperature, but its effect is apparently much smaller than the drop of temperature. Although the crack propagation is highly nonlinear with little qualitative distinction at various temperatures and loading rates, the time-temperature superposition principle seems to be quite suitable to characterize the material's viscoelastic behavior. Furthermore, the increase in specimen thickness tends to decrease the material's load-carrying ability per unit thickness, and this effect seems to be slightly more obvious than the loading rate.

The crack opening and blunting are the main reasons for the large vertical displacement field, and the intense strain zone which are present either above and below the crack surface or in front of the crack tip. These patterns are believed to be qualitatively similar over the entire test environment. Finally, for sharp cracks, the estimated displacement singularity using the continuum theory appears to be reasonably close to the analytical solution, which indicates the material's good resistance to dewetting.

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APPENDIX

Algorithm for Displacement Singularity Determination

Benthem (9) studied the problem where a quarter infinite crack in a half space (figure A.1) intersects with the free surface at right angles, and used the separation of variables method to evaluate the vertex singularity at the intersection point. He assumed

$$u_i = \sum_{k=1}^{\infty} r^{\lambda_u^k} h_i(\theta,\phi)_k \qquad \text{(A.1)}$$

and a corresponding set of expressions for σ_{ij} for an elastic material. If one only considers the vertical displacement along the line perpendicular to the crack plane, i.e. $\theta=\phi=\pi/2$, it yields to the first order of approximation

$$u_2 = D_2 r^{\lambda_u} \qquad \text{(A.2)}$$

which further leads to

$$\ln u_2 = \ln D_2 + \lambda_u \ln r \qquad \text{(A.3)}$$

The above equation can be utilized to estimate the displacement singularity, λ_u, for sharp crack tips by plotting $\ln u_2$ versus $\ln r$. If the crack is blunted, equation (A.3) is modified by subtracting half of the crack tip opening displacement, u_{20}, from the actual vertical displacement, u_2,

$$\ln(u_2 - u_{20}) = \ln D_2 + \lambda_u \ln r \qquad \text{(A.4)}$$

so that the displacement singularity can be evaluated in a similar manner.