JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 29, No. 5, September–October 1992

Acoustic Evaluation of Damage Characteristics in a Composite Solid Propellant

C. T. Liu*
Phillips Laboratory, Edwards Air Force Base, California 93523

This paper summarizes the current progress in characterizing the damage field near the tip of a crack in a composite solid propellant, using the acoustic-imaging technique. The effects of loading history on the damage characteristics near the crack tips are discussed. In addition, the limitations of the acoustic-imaging technique are discussed, and recommendations for future work are presented.

Introduction

COMPOSITE solid propellants are filled elastomers containing solid particles. Therefore, it is expected that on the microscopic scale a highly filled solid propellant can be considered a nonhomogeneous material. When this material is strained, depending on the magnitudes of the local stress and local strength, damage may be developed in the material. The damage developed in the material may be in the form of dewetting between the binder and filler particle, or in the form of microcracks and microvoids in the binder. The developed damage will not be confined to a specific location. Rather, it will diffuse into a relatively large area or zone. The growth of the damage in the material may take place by material tearing or by successive nucleation and coalescence of the microvoids. These cumulative damage processes are time-dependent and the main factors responsible for the time sensitivity of the strength degradation as well as the fracture behavior of the material. Therefore, to gain an advanced understanding of the fracture behavior and the effect of damage state on crack-growth behavior in solid propellants, a detailed knowledge of the characteristics of damage evolution is required.

During the past years, a considerable amount of work has been done in evaluating the damage field in a composite[1–4] solid propellant by the use of the acoustic-imaging technique. In these studies, the damage field in a composite solid propellant subjected to complex cyclic loading histories was investigated using precracked sheet specimens. The specimen's size was $7.62 \times 6.35 \times 0.508$ cm ($3.0 \times 2.5 \times 0.2$ in.). Three types of cracked specimens with three cracks, two cracks, and one crack, respectively, were considered. The cracks were 2.5 cm (1.0 in.) long and they were parallel to the longest side of the specimen and perpendicular to the loading direction. During the test, the Lockheed Missiles & Space Company's acoustic-imaging system was used to measure the damage characteristics in the specimen.

This paper summarizes the current progress in characterizing the damage field in a composite solid propellant subjected to complex loading histories using the acoustic-imaging technique. The effects of loading history and prestraining on the damage characteristics near the crack tips are discussed. In addition, the limitations of the acoustic-imaging technique are discussed, and recommendations for future work are presented.

Received March 21, 1991; revision received March 10, 1992; accepted for publication March 19, 1992. This paper is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

*Project Manager, OLAC PL/RCP. Member AIAA.

Testing

In the past, the Lockheed Research Laboratory's acoustic-imaging system was used to measure the attenuation difference in a scanning mode. Because acoustic imaging is conveniently performed in a water tank, a Lucite container was constructed to hold glycerol fluid in which a straining device could be immersed. This container was, in turn, immersed in a water tank. During the test, the acoustic wave of a wavelength short enough to exhibit quasioptical behavior was radiated from an insonifier combined with a plan concave polystyrene lens, which focused acoustic energy at a desired location in the material to be studied. Acoustic energy passing through the material was recovered by a receiver lens of similar geometry and configuration, which transmitted the acoustic energy to a receiving transducer. The receiving transducer converted the transmitted acoustic energy into a corresponding electrical signal which was stored in a computer for further data analysis.

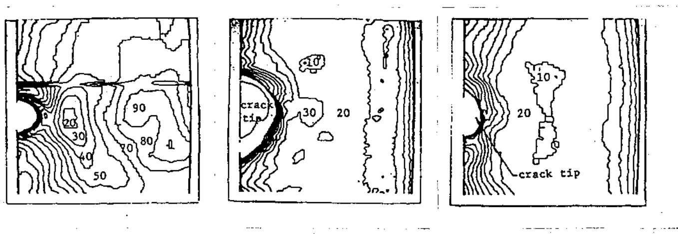
A two-dimensional acoustic image is generated in a common focal plane of the lenses by mechanical translation of the two lens/transducer units together in a plane normal to the acoustic transmission path. Each translation generates one scan line in the image. After each scan line has been completed, the scan mechanism steps one unit in elevation, and another line scan is performed. Approximately 512 data points are generated per scan line, and 100 lines are scanned per inch of test material. An ultrasonic frequency of 1.9 MHz is used in the test. A detailed description of the testing setup and some of the basic components used in the acoustic-imaging system can be found in Ref. 1.

The recorded experimental data were processed to create a visual indication of the energy absorbed in the material being inspected. A region of high ultrasonic absorption, i.e., a highly damaged area, will be shown as a dark area and a region of unattenuated ultrasonic wave will produce a light or white area with 255 shades of grey in between. The acoustic image at a given strain level was plotted in the form of isointensity contours of the transmitted acoustic energy I_t to enhance the resolution of the damage field. The results of these analyses are discussed in the following paragraphs.

Results and Discussion

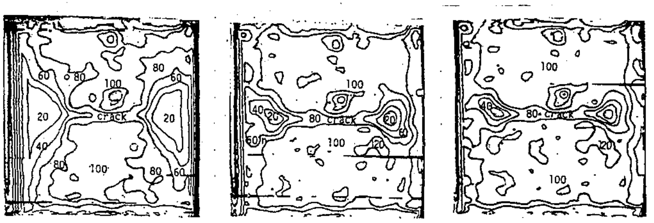
Before giving a detailed discussion of the experimental results, the basic damage mechanism in the solid propellant will be briefly discussed.

A composite solid propellant may be considered as a lightly cross-linked polymer, highly filled with coarse solid particles. When this material is subjected to external loads, it behaves like a viscoelastic material. Since a highly filled composite solid propellant consists of a large number of fine particles, on the microscopic scale it can be considered a nonhomogeneous material. When this material is stretched, highly nonhomoge-



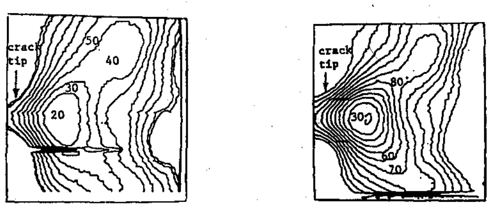
a) 3% strain b) 6% strain c) 3% strain

Fig. 1 Isointensity contour plots of acoustic image near the tip of the center crack (ϵ = 3%–6%–3%, Fig. 6 in Ref. 1).



a) 0% strain b) −1.5% strain c) 0% strain

Fig. 2 Isointensity contour plots of acoustic image near the crack tip (ϵ = 0%, −1.5%, 0%, Fig. 8 in Ref. 3).



a) Taken before the 10 strain cycles b) Taken after the 10 strain cycles

Fig. 3 Isointensity contour plots of acoustic image near the crack tip (ϵ = 0%, Fig. 8 Ref. 1).

neous local stress and strength fields can be developed in the material. Since the local stress and strength vary in a random fashion, the location and the degree of damage will also vary randomly in the material. The damage may be in the form of microcracks and microvoids in the binder, or in the form of binder/particle separation known as dewetting. When the microdefects are generated, the local stress will be redistributed. With time, additional microdefects can be generated. This time-dependent process of damage nucleation is due to the time-dependent processes of stress redistribution and microdefect generation. When the damage state reaches a critical value, the rigidity of the material is thereby reduced. Usually, this critical damage state coincides with the transition from linear response to nonlinear behavior of composite solid propellants. In the nonlinear region, depending on the solid propellant formulation and testing conditions, damage growth may take place as successive nucleation and coalescence of the microvoids or as material tearing. As the damage grows, it will eventually give rise to one or more dominant cracks that propagate rapidly to fracture. These damage processes are time-dependent and are the main factors responsible for the time sensitivity of the material response and fracture behavior in composite solid propellants.

Having briefly discussed the damage mechanisms in solid propellants, the acoustic-imaging test results which show the load history and time dependence of damage characteristics near the crack tip in a sheet specimen will be discussed.

Plots of isointensity contours of I_t as a function of the applied strain are shown in Fig. 1. In Fig. 1 the number between two contour lines is the range of I_t between the prior and the next intensity level. The small number indicates that the intensity of the transmitted acoustic energy is low, or the damage level is high. It should be mentioned that because of acoustic diffraction, the size of the apparent crack as shown in Fig. 1 is relatively larger than the actual crack. Referring back to Figs. 1a and 1b, it is seen that the size of the damage zone and the severity of the damage in the damage zone increase as the strain level increases. This phenomenon, under a monotonically increasing load condition, is expected because as the strain level increases the magnitude of the stress near the crack tip increases and, consequently, the severity of the damage and the damage zone size increases. When the specimen is unloaded from 6 to 3% strain, a comparison between Figs. 1a and 1c reveals that the damage zone size and degree of damage at 3% strain during unloading are higher than that at 3% strain during loading. This indicates that a large amount of damage can develop near the crack tip region when the strain is increased from 3 to 6% during the loading branch of the strain cycle. It is interesting to note that, when the applied strain is reduced from 6 to 3%, the size of the highly damaged region, $I_t = 10$, is increased. The increase in damage during unloading is probably due to a number of reasons. First, the increase in damage immediately after specimen unloading is believed to be related to the local stresses between the filler particles. For a highly filled solid propellant, when the applied stress is decreased, the local stresses between particles may still be high enough to cause additional damage and/or to increase the size of the existing voids. In other words, a nonsimple redistribution of stresses within the damage region takes place, resulting in new material damage and, thus, an enlarged damage zone. Second, due to the material's viscoelastic nature, the local time-dependent material response lags behind and is not in phase with the applied deformation, as pointed out by Williams[5] and Knauss.[6] The same reasoning can be applied to explain a similar phenomenon observed when a compressive strain is applied to the specimen. The effect of compressive strain on the damage characteristics near the crack tip is discussed next.

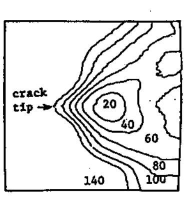
As reported in Ref. 3, a precracked sheet specimen with one center crack was used to investigate the effect of a compressive load on the damage characteristics near the crack tip. The specimen was first stretched to 6% strain and then was unloaded to 0% strain. The acoustic data at 0% strain is shown in Fig. 2a. After the specimen was imaged at 0% strain, a negative 1.5% strain, or a compressive strain of 1.5%, was applied to the specimen, and the acoustic data is shown in Fig. 2b. When the specimen was unloaded from −1.5 to 0% strain, the specimen was imaged again and the acoustic data is shown in Fig. 2c. A comparison of Fig. 2a with Fig. 2b reveals that the sizes of the highly damaged regions near the crack tips are reduced and the sizes of the less damaged regions between the crack and the upper and lower edges of the specimen are increased. This phenomenon is probably due to the reduction of the size of the voids under the compressive strain condition. The effect of compressive strain on the reduction of the highly damaged regions near the crack tip still exists even though the specimen was unloaded from −1.5 to 0% strain as shown in Fig. 2c. From Fig. 2b and Fig. 2c, it is seen that the sizes of the highly damaged regions near the crack tips are further decreased and the sizes of the less damaged regions in the specimen are relatively unchanged. This is probably due to the same reasons as those already discussed to explain why the damage magnitude near the crack tip increased when the specimen was unloaded from 6 to 3% strain. The effect of compressive strain on the damage characteristic was further demonstrated when the specimen was under cyclic loading, and this is discussed in the following paragraph.

The isointensity contours of I_t near the tip of the center crack at 0% strain before and after the specimen was subjected to an additional 10 small amplitude strain cycles, which has a maximum strain of 3%, are shown in Fig. 3. According to Fig. 3, the size of the damage zones is reduced as a result of the application of 10 additional cycles to the specimen. This indicates that, instead of increasing the amount of damage, the severity of the damage is reduced by the application of 10 additional strain cycles to the specimen. This phenomenon is believed to be related to the development of the residual compressive stress at the end of each strain cycle. The development of compressive residual stress under cyclic loading conditions was reported by Liu[7] in his study on the effect of cyclic loading sequence on cumulative damage and constitutive behavior in a composite solid propellant. It was found that the magnitude of the compressive residual stress depends on the maximum strain of the strain cycle; the higher the maximum cyclic strain, the higher the compressive residual stress. The existence of the compressive residual stress is believed to be a contributing factor, in addition to the time dependence of the material's deformation process, to the reduction of the microvoid size or the damage zone size, especially near the crack tip regions. The effects of these two factors on the damage characteristics in the specimen is now discussed.

At the end of each strain cycle, because large deformation occurs near the crack tip, the deformed material does not return to its original strain-free condition, even though the applied strain is zero. Thus, a compressive residual stress and tensile residual strain region is developed near the crack tip. The existence of the tensile residual strain near the crack tip will prevent the microcracks and microvoids, generated by previously applied strain, from closing in spite of the existence of the compressive residual stress field. In addition, due to the material's viscoelastic nature, a time scale or phase shift exists between the applied load and the microscopic (local) deformation of the material. Thus, some time is required to rearrange the microstructure, such as the movement of the filler particles in the material, to respond to the load. These may be the reasons why the damage zones still exist when the specimen is unloaded to 0% strain. However, as time elapses, microvoid size will decrease due to the time-dependent nature of the material deformation process. The decrease in microvoid size with increasing time should be manifested by the increase in I_t value. In other words, damage zone size as well as damage severity will decrease as the length of time is increased. This time dependence of damage characteristics, measured by the acoustic-imaging technique, is clearly indicated in Fig. 4. However, as shown in Ref. 2, when the specimen was held at 6% strain for 18 h and then unloaded to 0% strain, the acoustic-imaging data obtained at 0% strain indicated that the highly damaged regions near the crack tips still existed. This is clearly indicated in Fig. 5, and is different from what we have observed for the case when the specimen was held at 0% strain for 3 h. This indicates that the strain level at which the specimen is held for a period of time has a significant effect on the measured damage intensity and damage zone size using the acoustic-imaging technique.

The preceding discussion is centered on the load history and time effects on the damage characteristics in a precracked specimen. In the following paragraph, the effect of prestrain or predamage to the damage characteristics in a prestrained specimen is discussed.

As shown in Ref. 3, a virgin specimen without cracks was strained to 9% strain and then was unloaded to 3% strain. While the specimen was held at 3% strain, a crack was cut at the center of the specimen. The specimen was imaged before and after the crack was cut and the acoustic-imaging data are shown in Fig. 6. Figure 6a indicates that extensive damage was developed by the 9% strain and the damage intensity was relatively uniform in the specimen. The uniformly distributed damage intensity is an indication that the damage process is dominated by the damage nucleation process. In other words, the number of microvoids in the specimen increases with increasing strain level. This kind of damage nucleation and growth process is a typical process that has been observed in prestrained specimens. When a crack was cut in the specimen, the presence of a crack in the specimen will redistribute the stress in the specimen, especially near the crack tip region. The redistribution of stress will result in a modification of damage

a) 

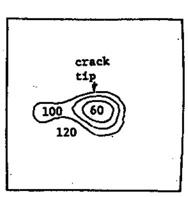
b) 

Fig. 4 Isointensity contour plots of acoustic image near the crack tip ($\epsilon = 0\%$, Fig. 7 in Ref. 1; part b was taken 65 h after part a).

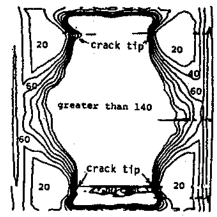
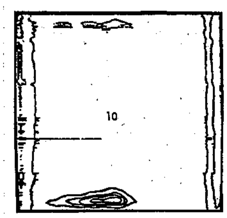
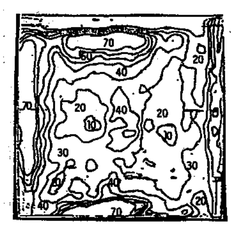


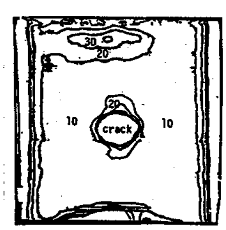
Fig. 5 Isointensity contour plots of acoustic images near the crack tip at 0% strain (after 18 h at 6% strain; Fig. 11 in Ref. 2).



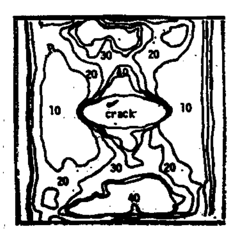
a) 3% strain, before the crack was cut



b) 3% strain, after a 1.27-cm crack was cut



c) 6% strain, crack length equal to 1.27 cm



d) 6% strain, crack length equal to 2.54 cm

Fig. 6 Isointensity contour plots of acoustic images of the specimen (prestrained specimen, a crack was cut at 3% strain, Figs. 6 and 7 in Ref. 3).

distribution as shown in Fig. 6b. By comparing Fig. 6a and Fig. 6b, it is seen that the contours of I_t are different. The difference arises mainly because the stress in the specimens is relieved to some extent in most areas except near the crack tip region, and consequently the size of the microvoids is reduced. When the strain level was increased from 3 to 6%, the damage intensity increased and the highly damaged region spread into a large area. A comparison between Fig. 6c and Fig. 6a reveals that the damage characteristics at the two different strain levels are close to each other. This indicates that the damage developed by prestraining still exists. It is interesting to note that after a crack was cut in the prestrained specimen, the damage characteristics in the specimen depended on the length of crack as shown in Figs. 6c and 6d. According to Figs. 6c and 6d, the damage intensity in the center regions between the crack and the upper and lower edges of the specimen depends on the crack length; a short crack length induces a relatively high and uniform intensity of damage. It is believed that a longer crack length will lead to a higher stress relieving in the aforementioned regions. In other words, a longer crack induces a relatively large "shielding" effect on the material in the center regions between the crack and the upper and lower edges of the specimen.

Conclusions

In this paper, we summarize some recent results of acoustic-imaging tests. Experimental data indicate that load-history and time have significant effects on the damage characteristics in a composite solid propellant. Therefore, caution should be exercised when interpreting the acoustic-imaging results or other nondestructive testing results to determine the damage state in solid propellants. Although these studies indicate that the use of the acoustic-imaging technique in detecting and monitoring damage evolution is promising, additional work needs to be performed to reduce the acoustic diffraction in the immediate neighborhood of the crack and to determine the relationship between the actual damage in the material and the measured acoustic-imaging parameter I_t.

Acknowledgment

This work was supported by the Office of Scientific Research, Air Force Systems Command. The author would like to express his appreciation to A. Romar for typing the manuscript.

References

[1]Liu, C. T., and Yee, R., "Evaluation of Cumulative Damage in a Composite Solid Propellant," *Proceedings of the 1986 Society for Experimental Mechanics Conference on Experimental Mechanics*, June 1986, pp. 729–736.

[2]Liu, C. T., "Investigating the Damage Field Near Crack Tips in a Composite Solid Propellant," *Proceedings of the 1987 Society for Experimental Mechanics Conference on Experimental Mechanics*, June 1987, pp. 453–461.

[3]Liu, C. T., "The Measurement of Damage in a Solid Propellant by Acoustic Imaging Technique," AIAA Paper 87-1703, July 1987.

[4]Liu, C. T., "On the Evaluation of Damage Field Near Crack Tips in a Composite Solid Propellant," AIAA Paper 88-2284, April 1988.

[5]Williams, M. L., "Fatigue-Fracture Growth in Linearly Viscoelastic Material," *Journal of Applied Physics*, Vol. 38, No. 11, Oct. 1967, pp. 4476–4480.

[6]Knauss, W. G., "Delayed Failure—The Griffith Problems for Linearly Viscoelastic Material," *International Journal of Fracture Mechanics*, Vol. 6, No. 1, March 1970, pp. 7–20.

[7]Liu, C. T., "Effects of Cyclic Loading Sequence on Cumulative Damage and Constitutive Behavior of a Composite Solid Propellant," *Proceedings of the AIAA/ASME/ASCE/AHS 28th Structures, Structural Dynamics, and Materials Conference*, AIAA, Washington, DC, April 1987, pp. 847–855.

Earl A. Thornton
Associate Editor