Monitoring Damage Characteristics in a Filled Elastomer under Cyclic Loads Using X-Ray Techniques

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Abstract

In this study, the damage fields near the crack tip in edge-cracked sheet specimens subjected to a constant strain rate of 0.05 min^{-1} were investigated using real-time radiographic techniques. During the tests, Lockheed-Martin Advanced Technology Center's high-energy real-time x-ray system (HERTIS) was used to monitor damage initiation and evolution processes near the crack tip. The experimental findings indicate that x-ray technique is a promising technique to monitor damage evolution during crack propagation.

Introduction

In recent years, a considerable amount of work has been done in studying damage characteristics in highly filled polymeric materials, using nondestructive testing techniques (1-4). The importance of these studies stems from the fact that damage can significantly affect the constitutive and crack growth behavior in these materials. Experimental findings reveal that damage, expressed in terms of attenuation of the acoustic energy, increases with increasing strain rate, and the critical damage is relatively insensitive to the strain rate. They also reveal that the damage state correlates well with the constitutive behavior of the material. In addition, for pre-cracked specimens, the damage state near the tip of a stationary crack is highly dependent on the loading history.

In this study, the damage field near the crack tip in edge-cracked sheet specimens subjected to cyclic loads was investigated using x-ray techniques. During the tests, Lockheed Martin Advanced Technology Center's high-energy real-time x-ray system was used to monitor damage initiation and evolution processes near the crack tip. The recorded x-ray data were processed to create a visual indication of the energy absorbed in the material. A region of high absorption (i.e., a low damage area) produced a dark area, whereas a region of low absorption produced a light or white area, with 254 shades of gray in between. The experimental data were analyzed and the effect of cyclic loads on the damage state near the crack tip is discussed.

The Experiments

In this study, an edge crack was cut at the left side of the sheet specimen with a razor blade. The specimen was made of a highly filled elastomer, containing 86% by weight of hard particles

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14. ABSTRACT
In this study, the damage fields near the crack tip in edge-cracked sheet specimens subjected to a constant strain rate of 0.05 min-1 were investigated using real-time radiographic techniques. During the tests, Lockheed-Martin Advanced Technology Center’s high-energy real-time x-ray system (HERTIS) was used to monitor damage initiation and evolution processes near the crack tip. The experimental findings indicate that x-ray technique is a promising technique to monitor damage evolution during crack propagation.

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embedded in a rubber matrix. The specimen was subjected to an incremental cyclic-strain loading condition, which had a triangular shape and seven strain cycles. The minimum strain level for each cycle is 0% and the maximum strain level for each cycle were 1.75%, 4.55%, 9.5%, 9.5%, 10%, 15%, and 19%. After the last strain cycle, the specimen was pulled to fracture at a constant strain rate of 0.05 min^{-1} that was the same strain rate used during the cyclic-strain test.

During the tests, Lockheed Martin Advanced Technology Center's HERTIS was used to investigate the characteristics of the damage initiation and evolution processes. The HERTIS setup for x-raying the specimens is shown in Fig. 1. The specimen was placed between the x-ray radiation source and the x-ray camera, with a source-to-specimen distance of 42.5 inches and a source-to-scintillator distance of 44 inches. X-ray intensity is attenuated by the material as described by the equation $I_x/I_i = e^{(-\mu x)}$, where I_x is the x-ray intensity passing through the material, I_i is the initial x-ray intensity entering the material, e is the natural exponential, μ is the linear x-ray attenuation coefficient, and x is the path length of the x-rays in the specimen. Since the material is a composite material, μ_x is actually the sum of all the μ_x's for the constituent materials, including air for voids and cracks. X-rays not absorbed or scattered by the specimen are absorbed by the x-ray scintillator screen, which converts the x-rays into a visible light image. This image is viewed by a low-light-level TV camera through a mirror placed at 45^o to the x-ray beam. The TV camera converts the light image into an electrical signal that is digitized, stored, and displayed on a monitor. The x-ray images are digitized to 1024 x 1024 pixels over a 4 x 4 inch field-of-view, with 8 bits or 256 linear intensity levels. A detailed description of the HTRIS system can be found in Reference 5. When conducting the x-ray test, the 160kV x-ray source was set to 75 kV, 0.5 mA, with a 0.4 mm focal spot, without filters, and a 25-second exposure time. The combination of pixel size, geometric unsharpness, and electron range produced an effective system resolution of 0.004 inch (100μm) in the specimen. The recorded x-ray data were processed to create a visual representation of the energy absorbed in the material. A region of high absorption (i.e., a low damage area) was shown as a dark area, whereas a region of low absorption produced a light or white area, with 254 shades of gray in between. To enhance the resolution of the damage field, the x-ray data were analyzed to delineate the damage field ahead of the crack tip and to generate contour plots of the damage intensity.

Results and Discussion

A highly filled polymeric material, which consists of a large number of fine particles, on the microscopic scale, can be considered inhomogeneous. When subjected to external loads, it behaves like a viscoelastic material and highly inhomogeneous local stress and strength fields can develop. Because of the particle's high rigidity relative to the binder, the local stress is significantly higher than the applied stress, especially when the particles are close to each other. Experimental findings reveal that for a densely filled polymeric material, the stresses tending to cause local failure are nearly equal at the binder/particle interface and in the binder itself; and the failure, either cohesive failure in the binder or adhesive failure at the interface, occurs when either the local binder rupture strength or the interfacial bond strength is exceeded. The local stresses are greatest when the particles are close to each other and their line of center coincides with the direction of the external load. Since local stress and strength vary in a random fashion, the failure site in the material also varies randomly and does not necessarily coincide with the maximum stress location. In other words, the location and degree of damage will also vary randomly in the material. The damage may appear in the form of microcracks and microvoids in the binder, or in the form of particle/binder separation known as dewetting. When the particle is dewetted, the local stress will be redistributed. With time, additional particle/binder separation and vacuole formation takes place. This time-dependent process of dewetting nucleation, or damage nucleation, is due to the time-dependent processes of stress redistribution and particle/binder separation. Depending on the formation of the material and the testing condition, damage growth may take place as material tearing or by successive nucleation and coalescence of the microvoids. These damage initiation and evolution processes are time-dependent, and are the main factor responsible for the time-dependent strength degradation and fracture behavior of the material.

The above paragraph discussed the damage mechanisms in the particle-filled polymeric material. In order to determine the damage intensity and the damage fields near the tip of the propagating crack, real-time test data were analyzed. The results of the analyses are discussed in the following paragraphs.

In data analysis, high x-ray intensities corresponding to high damage regions were digitally processed to be displayed as black regions. Typical digital real-time x-ray image as a function of strain are shown in Fig. 2. When the specimen is strained, the high intensity of stress near the crack tip will damage the material. As the material is damaged, the x-ray image shows a dark area near the crack tip. Initially, the size of the dark area or the size of the damage zone increases with increasing applied strain level. This phenomenon is expected because the local stresses near the crack tip increases with increasing applied strain level. However, the damage zone size will not continuously increases with increasing applied strain level. Real-time x-ray data reveal that the damage zone size starts to decrease when a certain applied strain level is reached. This applied strain level is close to the strain level corresponding to the maximum applied stress. Since the applied stress will continuously decrease beyond the maximum applied stress, the local stress near the crack tip will also decrease. Since damage zone size is directly proportional to the local stress near the crack tip, the decrease in applied stress results in a reduction in local stress near the crack tip, which, in turn, results in a reduction in damage zone size.

Figure 3 shows the contours of transmitted x-ray energy near the crack tip at three different applied strain levels, 0%, 1.75%, 0%, 4.45%, and 0%, which corresponding to the first two cyclic loading cycles. In this figure, the number between two contour lines is the minimum intensity level of a range of I_t between the minimum intensity level and the next intensity level. A small number indicates that the intensity of the transmitted x-ray energy is high or the damage is high. These contour plots show the details of the size and shape of the damage zone as well as the damage intensity inside the damage zone. According to Fig. 3, the size of the damage zone and the intensity of damage in the damage zone increase when the applied strain level is increased from 0% to 1.75%. By comparing Fig. 3a with Fig. 3c and Fig. 3e at 0% applied strain, the damage distribution near the crack tip are different as a result of increasing the damage intensity and changing the microstructure by applying higher strains of 1.75% and 4.45% to the specimen. It is interesting to note that the damage zones still exist when the specimen is unloaded to 0% strain. This phenomenon is probably related to the time-dependent deformation process. At the end of each strain cycle, because large deformation occurs near the crack tip, the deformed material doesn't return to its original strain-free condition even though the applied strain is 0%. 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, some time is required to rearrange the microstructure, such as the movement of filler particles within the material, to respond to the load. It is expected that, as time elapses, microvoid size will decrease due to the time-dependent nature of the material deformation process. Consequently, the decrease in microvoid size with increasing time should be manifested by the decrease in damage zone size and damage intensity as the length of time is increased.

A comparison of Fig. 3b and Fig. 3d reveals that not only the crack propagates but also the damage zone size and the intensity of the damage increase under the higher strain; however, the damage intensity away from the crack is relatively unchanged. From Fig. 3d, it is also noted that the damage gradient near the crack tip is very steep. The region that has a steep damage gradient is restricted to a very small area in the immediate neighborhood of the crack tip. When the applied strain level is low, the damage outside the steep damage gradient area is negligible. As the applied strain level is increased, the damage gradient is decreased and the size of the highly damaged region is increased as shown in Fig. 3d. These experimental findings, obtained from real-time x-ray data, are consistent with experimental findings reported by Smith et al (6) in their study of local strain distribution near the crack tip in a highly filled polymeric material. As pointed out by Smith and Liu, the intense strain zone, or the highly strained region, ahead of the crack tip is very small and the strain level outside the intense strain is approximately equal to the applied strain level. Under this condition, it is expected that if the applied strain level is below a critical value, it can be assumed that no significant damage will develop outside the intense strain zone.

Figures 4a and 4b show the damage distribution near and away from the crack tip under a constant applied strain of 9.5%. According to Fig. 4, it is seen that under the constant strain condition, the crack propagates and the damage zone size and the intensity of damage increase. It is known that for a viscoelastic material the stress in the material will relax under the constant strain condition. The growth of the crack and the increase in the damage zone size near the crack tip is probably due to the material's viscoelastic nature. In other words, a time scale or phase shift exists between the applied stress and the local stress in the material, especially near the crack tip. Under this condition, even the global stress starts to relax but the local stress near the crack tip is still high enough to propagate the crack.

Conclusions

The damage characteristics near the crack tip in a highly filled elastomer subjected to cyclic loads was investigated using x-ray radiograph techniques Experimental findings reveal that damage zone size and intensity of damage in the damage zone are highly dependent on the load history and the microstructure of the material. Although this preliminary study indicates that the x-ray technique is a promising technique to monitor damage evolution during crack propagation, caution should be exercised when interpreting the x-ray data or other nondestructive testing results to determine the damage state in highly filled elastomer materials.

References

(1) Liu, C. T. and Yee, R., “Evaluation of Cumulative Damage in a Composite Solid Propellant” Society of Experimental Mechanics 1986 Spring Conf. June, 1986, pp.729-736.
(2) Liu, C. T., “ Evaluation of Damage Fields near Crack Tips in a Composite Solid Propellant,” Journal of Spacecraft and Rockets, Vol.28, No.1, 1991, pp. 64-70.
(3) Liu, C.T. and Tang, B. “Investigating Cumulative Damage in a Highly Filled Polymeric material,” Mechanics of Materials and Structures Studies in Applied Mechanics, Vol.35, 1994, Elsevier Science, pp.86-100.
(4) Tang, B., Liu, C. T., and Henneke, E. G., “Acoustic-Ultrasonic Technique Applied to the Assessment of Damage in a Particulate Composite,” Journal of Spacecraft and Rockets, Vol.32, No.5, 1995, pp. 866-869.
(5) Sklensky, A.F. and Buchanan, R. A., “Sensitivity of High-Energy Real-Time Radiography with Digital Integration,” ASTM, STP 716, 1985, pp.315-329.
(6) Smith, C. W. and Liu, C. T. “Effects of near Tip Behavior of Particulate Composites on Classical Fracture Concepts,” Journal of Composites and Engineering, Vol.1, 1991, pp249-256.