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C.T. Liu, "Application of Real-time X-Ray Technique to Monitor Damage Process in a Particulate Filled Elastomer"

2d Workshop on Structural Health Monitoring **(Public Release)**

Application of Real-Time X-Ray Technique to Monitor Damage Process in a Particulate Filled Elastomer

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ABSTRACT

The damage initiation and evolution processes in an edge-cracked sheet specimen subjected to a constant strain rate were investigated using real-time x-ray techniques. The specimens were made of a particulate composite material containing hard particles embedded in a rubber matrix. The x-ray data were analyzed and the results are discussed.

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 (1-3). The importance of these studies steams from the fact that damage can significantly affect the constitutive and the crack growth behavior in these materials. Experimental findings reveal that damage, expressed in terms of the 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 a constant strain rate of 1.0 min^{-1} was investigated using real-time radiographic techniques. During the tests, Lockheed-Martin Research Laboratory's high-energy real-time x-ray system (HERTS) was used to monitor damage initiation and evolution processes near the crack tip. The experimental data were analyzed and the results are discussed.

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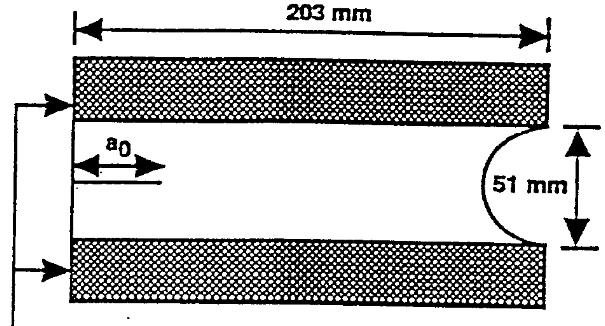


Fig. 1 Figure 1 Specimen geometry.

THE EXPERIMENTS

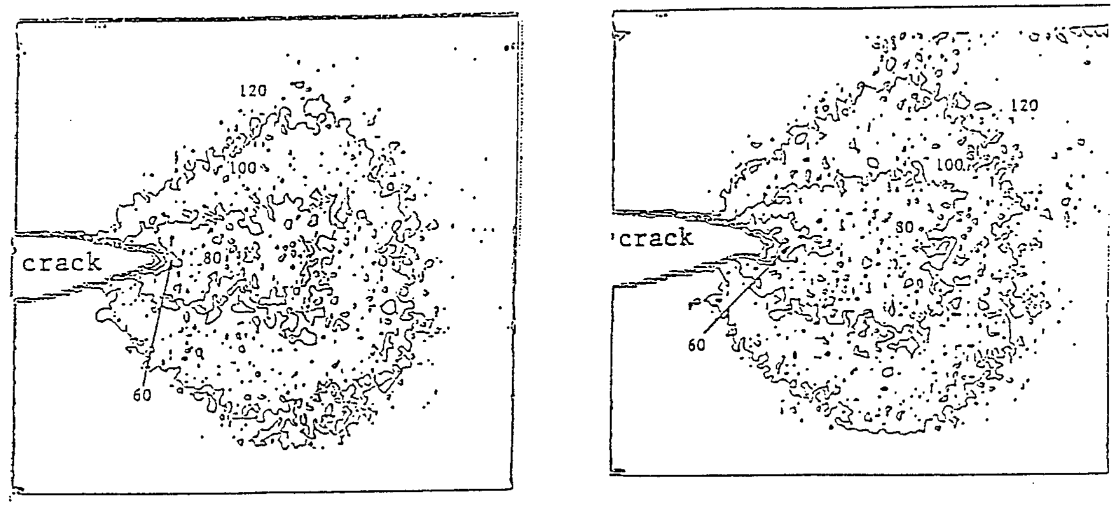
The damage field near the crack tip in edged-cracked sheet specimens subjected to a constant strain rate of 1.0 min^{-1} was investigated using real-time x-ray techniques. The specimens were made of a particulate composite material, containing hard particles embedded in a rubbery matrix. Prior to testing, a 23-mm crack was cut with a razor blade at the edge. The specimen geometries are shown in Fig. 1. During the test, Lockheed-Martin Research Laboratory's high-energy real-time x-ray system (HERTS) was used to investigate the characteristics of the damage field near the crack tip. The specimen was placed between the x-ray radiation source and the x-ray camera. The x-ray image exits from the specimen and strikes the screen that is in front of the x-ray camera. The screen converts the x-ray image into a light image. This image is reflected into a low-light-level television camera by a mirror placed at 45° to the beam in the back of the camera. This isocon TV camera then converts the light image into an electronic signal that can be routed into the main monitor and into the video tape recorder. A detailed description of the HERTS system can be found in Reference 4. 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) will be shown as a dark area, whereas a region of low absorption will produce a light or white area, with 254 shades of gray in between. Also, the x-ray image at a given applied strain level can be plotted in the form of iso-intensity contours of the transmitted x-ray energy to enhance the resolution of the damaged field.

RESULTS AND DISCUSSION

A highly filled polymeric material which consists of a large number of fine particles, on the microscopic scale, can be considered nonhomogeneous. When this material is stretched, the different sizes and distribution of the filler particles, the different crosslinking density of the polymer chains, and the variation of the bond strength between the particles and the binder can produce highly nonhomogeneous local stress and strength fields. 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. Since local stress and strength vary in a radom 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-sensitivity of the strength degradation as well as the 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.

Figure 2 shows the contours of transmitted x-ray energy near the tip of a propagating crack under the constant strain rate condition. 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 that 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. 2, the size of the damage zone and the intensity of damage in the damage zone increase with increasing applied strain level, and 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 intensity 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. 2. These experimental findings, obtained from real-time x-ray data, are consistent with experimental findings reported by Liu (5) and 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.



(a) Time = 4.27 sec

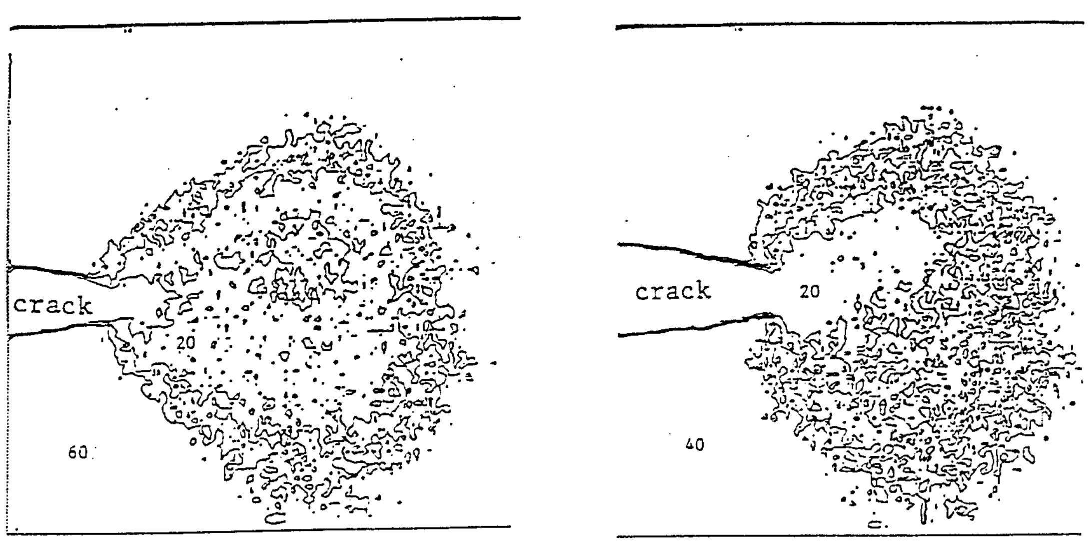
(b) Time = 5.33 sec

Figure 2 Iso-intensity contour plots of the x-ray energy transmitted through the specimen (without predamage).

In the above paragraph, we discussed the damage field near the crack tip when the crack propagates in a specimen without pre-damage. In the following paragraph, we will discuss the damage field near the crack tip when the crack propagates in a specimen with a pre-damage near the center of the specimen.

Figure 3 shows the contour plots of I_t near the tip of the crack in the specimen with pre damage. According to Fig. 3, when the applied strain level increases, the damage intensity near the crack tip and inside the damage zone also increases. At 8% applied strain level, small voids are developed near the center of the pre-damage zone. The effect of pre-damage zone on the damage characteristics near the crack tip increases with increasing applied strain level or time as a result of interaction between the damage fields at the crack tip and in the pre-damage zone. Experimental data reveal that when the crack starts to propagate, the pre-damage zone has no significant effect on the damage characteristics near the crack tip. The lack of interaction between the two damage fields is because the distance between the crack tip and the pre-damage zone is relatively large. However, as the crack propagates closer to the pre-damage zone, the effect of the pre-damage zone on the crack tip damage characteristics increases especially when the crack tip reaches the center of the pre-damage zone where small voids developed. The crack tip is severely blunted and its shape is highly irregular as shown in Fig. 3. As time elapses, the damage zone size decreases as a result of both global unloading of the speciman and local unloading near the crack tip. After the specimen broke, the material relaxes under a no loading condition and the size of the void decreases, and ,eventually, the surfaces of the particle and the void rejoin. Consequently, the x-ray technique can not measure the damage, resulting in the disappearance of the damage fields.

A plot of crack length, a, versus time, t, is shown in Fig. 4. From Fig. 4, it is seen that when time is between 0 second and 4 seconds, there is no significant difference in crack growth behavior between the specimens with and without pre-damage. This is because as mentioned earlier the distance between the crack tip and the pre-damage zone is large and there is no significant effect of the pre-damage on the damage field near the crack tip. When the crack propagates into the pre-damage zone at about 4 seconds, the crack propagates slower in the specimen with pre-damage than in the specimen without pre-damage as a result of the decrease in local stress at the crack tip. Since the crack growth behavior is controlled by the local stress at the crack tip, the decrease in local stress will result in a decrease in crack growth rate. As the crack propagates into the center of the pre-damage zone, the crack tip is highly blunted, and the local stress will significantly decrease. However, the crack growth rate is not decreased and the crack propagates with a high velocity through the pre-damage zone. This is because the material inside the pre-damage zone is severely damaged and will not provide any resistance to the growth of the crack.



(a) Time = 4 sec

(b) Time = 5 sec

Figure 3 Iso-intensity contour plote of the x-ray energy transmitted through the specimen (with predamage).

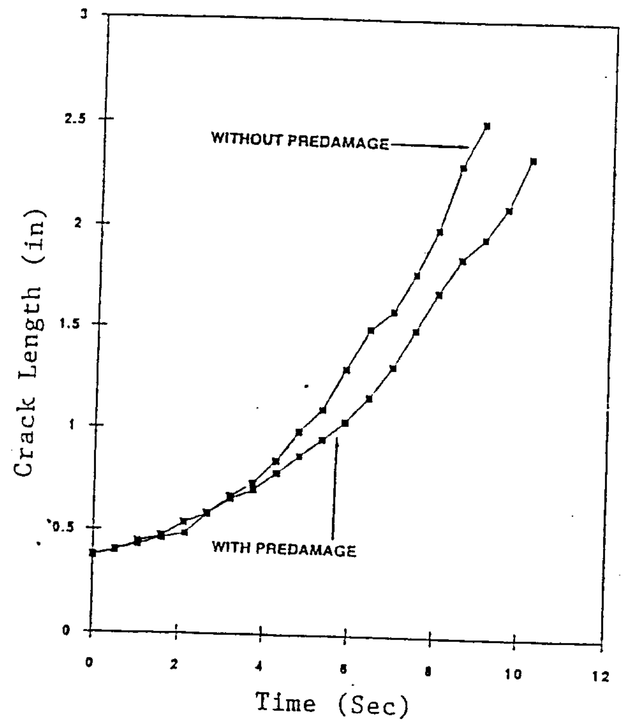


Figure 4 Crack length versus time.

In order to investigate the effect of pre-existing damage on the crack growth behavior in the particulate composite material, the crack growth rates da/dt as a function of time were calculated. In calculating da/dt, two methods, the secant and the polynomial, were used. In the secant method, the crack growth rate was computed by calculating the slope of a straight line connecting two adjacent a versus t data points. The calculated average crack growth rate was assigned at a point midway between each pair of data points. In the polynomial method, an nth order polynomial function was used to fit the a versus t data. The crack growth rate at a given time was calculated by taking the derivative of the fitted function at a given data point.

The determination of the crack growth rate requires an analysis of discrete date relating the instantaneous time,t, to the corresponding crack length,a. Due to nonhomogeneous nature of the particulate composite material, the measured data shows a considerable scatter. Therefore, it is anticipated that a smooth and steadily increasing relationship between the crack growth rate and time is difficult to obtain and the different methods of da/dt calculation may result in different solutions. From the results of the crack growth rate calculation, the secant method introduces a pronounced fluctuation of da/dt. The fluctuation of da/dt is consistent with experimental observation. Based on experimental evidence, in general, the crack does not grow in a continuous and smooth manner. During the crack growth process, crack growth rate both accelerates and decelerates. Therefore, the secant method appears to provide the best estimate of both the actual crack growth process and the actual crack growth rate. On the other hand, the smooth action introduced by the polynomial method will result in a continuous smooth crack growth curve Therefore, the polynomial method may mask the inherent variability of the crack growth rate by smoothing the data. However, the smooth crack growth curve obtained from the polynomial method can be considered as the average crack growth curve.

Plots of crack growth rate versus time are shown in Figs. 5 and 6. Figure 5 reveals that, based on the secant method of da/dt calculation, a pronounced fluctuation of crack growth velocity occurs during the entire time of crack growth. In other words, the crack growth process consists of a slow-fast-slow phenomenon which is highly nonlinear. The fluctuation of the crack growth rate is closely related to the local damage near the crack tip as discussed earlier. Figure 5 also shows the effect of pre-existing damage on crack growth behavior. When the time is less than 4 second, there is no significant difference in the crack growth rate when the crack propagates in the specimens with and without pre-damage. However, after 4 seconds, the difference in crack growth rates in the specimens with and without pre-damage increases with time. This phenomenon is clearly indicated in Fig. 6 when the crack growth rate was calculated by the polynomial method.

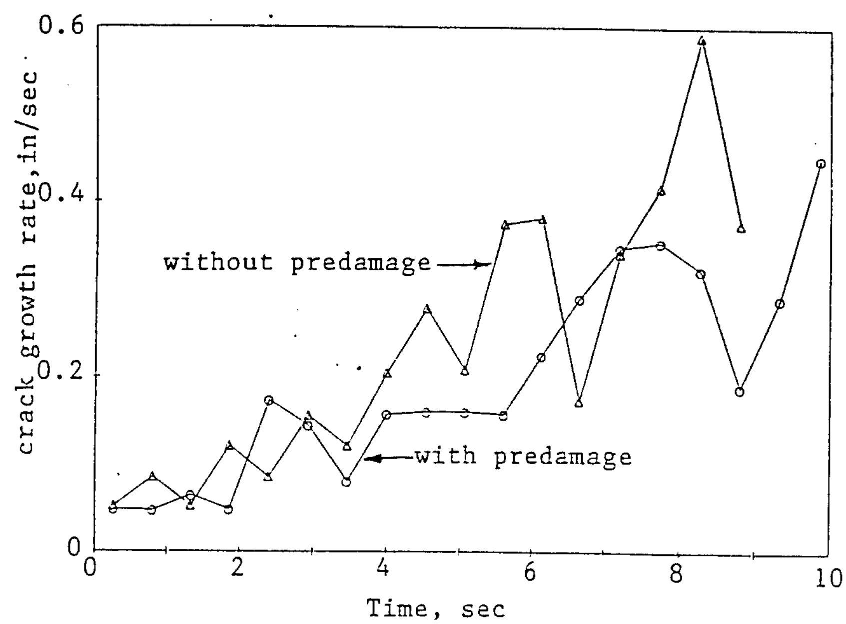


Figure 5 Crack growth rate versus time
(secant method).

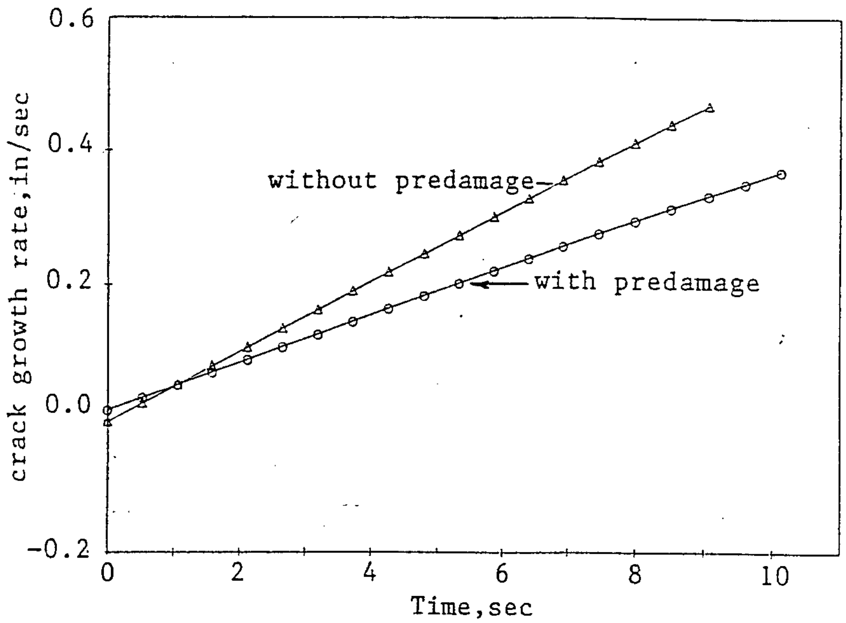


Figure 6 Crack growth rate versus time (polynomial method).

CONCLUSIONS

The damage characteristics near the crack tip in a particulate composite material subjected to a constant strain rate were investigated using real-time x-ray techniques. Experimental findings reveal that damage zone size and the intensity of damage inside the damage zone increase with increasing time, and pre-damage does affect the crack growth behavior in the material. It also reveals the real-time x-ray technique is a promising technique to monitor damage initiation and evolution processes in the particulate composite material

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