THERMOGRAPHIC DETECTION OF LOCAL HEATING DURING CYCLIC LOADING

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Thermography, originally designed for medical purposes, can be used to observe and sometimes predict fatigue damage in materials undergoing cyclic loading. In this study, fatigue tests were performed on steel, fiberglass, and aluminum while the samples were observed with a scanning infrared camera. Thermograms of surface temperature distributions are presented and compared as to degree of localization of temperature distribution and the time it takes for a temperature rise to appear.

Fatigue damage occurs in many materials when they are under the action of cyclic loading. Even when such loading does not reach the yield stress of the material under static conditions, the material incurs physical damage and eventually fails completely. Such failures are sometimes catastrophic, as in the case of an airplane structure in flight. The common technique for avoiding such failures is the periodic replacement of parts subjected to cyclic loads. These replacements are often unnecessary, although parts sometimes fail before they are scheduled for replacement. It would be desirable therefore to have some means of checking on the condition of parts undergoing cyclic loading while they are in service to determine whether they should be replaced. Possibly, such monitoring of critical structures could prevent loss of life and equipment.

Heat is generated in materials undergoing cyclic loading and in front of running fatigue cracks in materials by hysteresis effects (1). By observing the resulting temperature distribution in a sample undergoing cyclic loading, one should be able to locate areas of high stress, as indicated by hysteresis energy generation, and, possibly, to predict the location of the greatest fatigue damage in the sample and the location of the eventual failure. Although there are several methods of monitoring temperatures, thermography seems particularly well suited to the present problem. The radiation emitted from a surface is a function of its temperature. In thermography, a scanning infrared detector (camera) is used to convert this radiation into a visual image, which then represents the temperature distribution of the surface under study. For some time now the scanning infrared camera has been used in the medical profession as a research and diagnostic tool (2). Thermography has also been used in some areas of static nondestructive testing to locate material flaws and likely locations of weakness (3). However, little use has been made of the scanning infrared camera in fatigue studies to date (4). It is the purpose of this study to apply thermography to several fatigue tests of various materials and observe the temperature distributions of the samples. In this way, likely locations for the eventual fatigue damage should be observable before such damage actually becomes visible.

METHODS

The scanning infrared camera used in this study is shown in Figure 1. It consists of a scanner, a recorder, and a camera. The scanner was designed to detect radiation in the 8μ to 14μ wavelength range using a liquid nitrogen-cooled mercury cadmium telluride detector. One scan of the viewing field takes 4.5 sec and results in 525 horizontal lines each containing 525 elements. The detected radiation is then converted to a visual image in the recorder and displayed on a cathode-ray tube, where it can be photographed for a permanent record. This photograph, a visualization of the surface temperatures of the object of interest, is termed a "thermogram". An internally-generated reference scale also appears in the thermograms as an indication of the temperature range covered in each case. The temperature level and range are adjustable, at the recorder, to cover 60 F to 120 F ranges which may vary from one to 20 degrees.

Samples were stressed cyclically using the deflection-controlled, plate-flexure testing machine shown in Figure 2. The maximum deflection of each cycle can be adjusted up to 2 inches, and the rate of flexure is variable from 750 to 2000 cycles per minute. In Figure 2, a sample is clamped in the tester in the undeflected position. The scanner, positioned in front of the tester, then views the sample through a 45° mirror. Thermograms were made at various intervals while the sample was cycled until failure occurs. Periodically, visual inspections were made to determine the extent of surface damage around stress concentrations.

Samples of the three materials with which this study was concerned are shown in Figure 3. All samples were 2 inches wide and 12 inches long. As seen in Figure 3, the left end of each was clamped in the testing machine and the other end was deflected. The steel and fiberglass samples were 0.125 inches thick, while the aluminum sample was 0.100 inches thick. Saw cuts were made in each sample to produce stress concentrations and, hence, control the location of the fatigue damage. Attention could then be focused around the saw cuts in the thermograms and visual inspections made without danger of missing important information elsewhere on the samples. Since the scanning infrared camera is calibrated for use with blackbodies, it was necessary to paint the metal samples flat black to increase their emissivities to nearly unity in the 8-14μ wavelength range. The damage incurred during the fatigue tests is visible in Figure 3, a picture taken after the tests were made. The steel and aluminum cracked cleanly, with the former fracturing completely. The fiberglass did not display such behavior; instead small white spots in the sample indicated failure of the epoxy-matrix material.

RESULTS

The single-notched steel sample was tested at a maximum nominal bending stress level of approximately 40,000 pounds per square inch at a rate of 1700 cycles per

Figure 1. Scanning infrared camera showing scanner (left) and recorder (right).

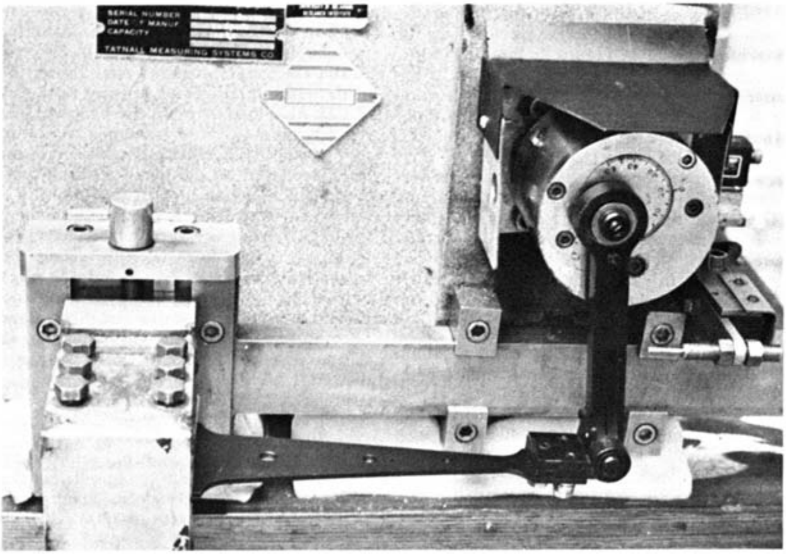

FIGURE 2. Tatnall-Krouse plate-flexure fatigue-testing machine.

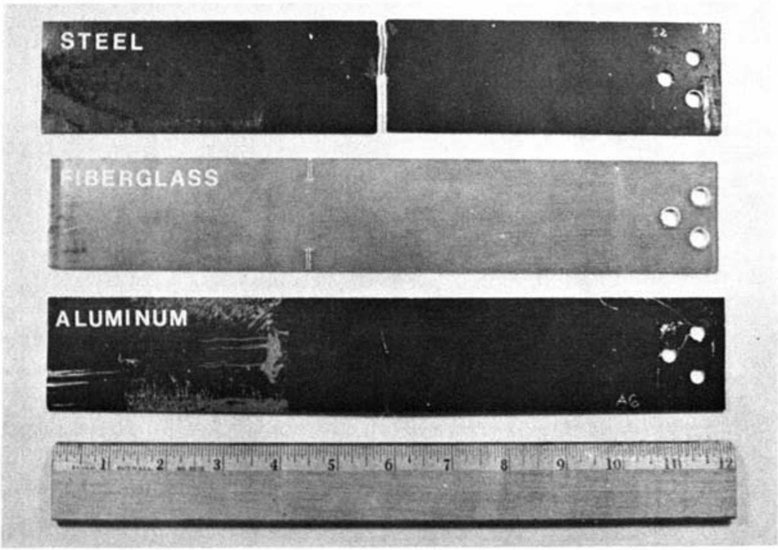

FIGURE 3. Fatigue samples.

min. This stress figure does not reflect the rise in stress around the saw cut due to the stress concentration. Figure 4 presents three of the resulting thermograms. Figure 4a shows the steel sample after only 1800 cycles. As can be seen from the reference scale, the temperature range covered in the thermogram is from 70 F, below which everything appears black, to 82 F, above which all temperatures are white. The reference temperatures have been corrected on the thermograms because the scale was slightly out of calibration. Room temperature was 65 F during this test. In Figure 4 the clamping vise of the fatigue tester is at the left, and the deflected end at the right. As can be seen, some heating had begun around the saw cut, where the stress was highest.

Figure 4b shows the same sample at about 13,300 cycles. Here the temperature range was 70 F to 83 F, and it can be seen that the edge of the saw cut was hotter than it was in Figure 4a, and that the region of elevated temperature was larger. Visual inspection at this time revealed no evidence of damage to the sample. At about 20,000 cycles, a crack appeared at the saw cut and began to propagate across the sample. Figure 4c, taken at 30,300 cycles, shows evidence of still higher surface temperatures and a greater heated region. At this point, the tip of the crack was observed to be about ½ inch from the lower edge of the sample, as seen in the thermogram. It can be seen in this thermogram that the sample had cooled off behind the tip of the crack; this region had already fractured and was no longer under high stress. The steel sample finally fractured completely at 35,800 cycles.

Figure 5 shows two thermograms taken during the test of the fiberglass sample, which had two saw cuts to induce stress concentrations. Room temperature during this test was 72 F. Figure 5a, covering 74 F to 87 F, was made after about 28,600 cycles at a maximum stress of 7500 psi. The sample was flexed at a rate of 2000 cycles per min. Early in the test, heating was observed at both of the saw cuts, as would be expected from the stress concentrations

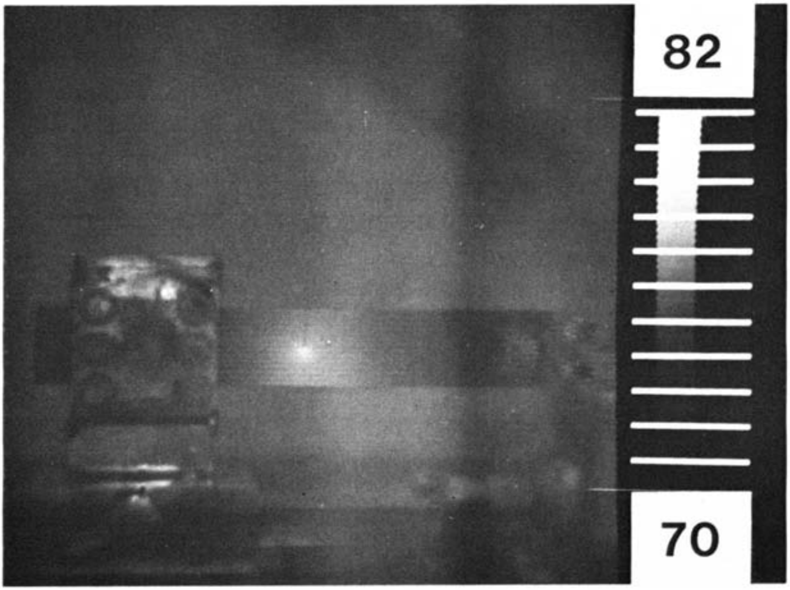

FIGURE 4a. Steel sample at 1800 cycles.

there. However, the stress level was not high enough to fracture the sample; damage to the epoxy matrix was limited, as seen in Figure 3. Eventually, the temperature field reached a steady state, which is shown in Figure 5b taken at 109,000 cycles. Here the maximum temperatures indicated are about 92 F. The sample was allowed to run in this manner for another 20,000 cycles and no further temperature changes were indicated, although visual signs of damage were increasing very slowly.

The aluminum sample was cycled under a maximum stress of 23,300 psi at a rate of 1900 cycles per min. Figure 6 shows the single-notched sample after almost 30,000 cycles. At this point a crack was propagating across the uncut region of the aluminum. The temperature rise caused by the high stress in this case resulted in a very blurred temperature field which gave only a general indication of the location of the maximum fatigue damage in the sample. The warmest region, as shown in Figure 6, was only about 5 F above room temperature, which was 79 F. The test was terminated before the sample failed completely.

DISCUSSION

In this study three materials of very different properties have been fatigue-tested using the scanning infrared camera to observe the heating associated with local stress concentrations. In each case, the heating resulted in an observable temperature increase which seemed to be centered about the point of highest stress. This temperature increase was localized to a different degree in each sample, as can be seen from the thermograms. The fiberglass displayed the greatest localization, while the aluminum showed poor localization of the temperature field. The degree of localization should be a function of the geometry of the sample and the heat-conducting ability of the material as indicated by its thermal conductivity. Since the geometry of the three samples was almost identical, the results in the thermograms should reflect the effect of thermal conductivity on the

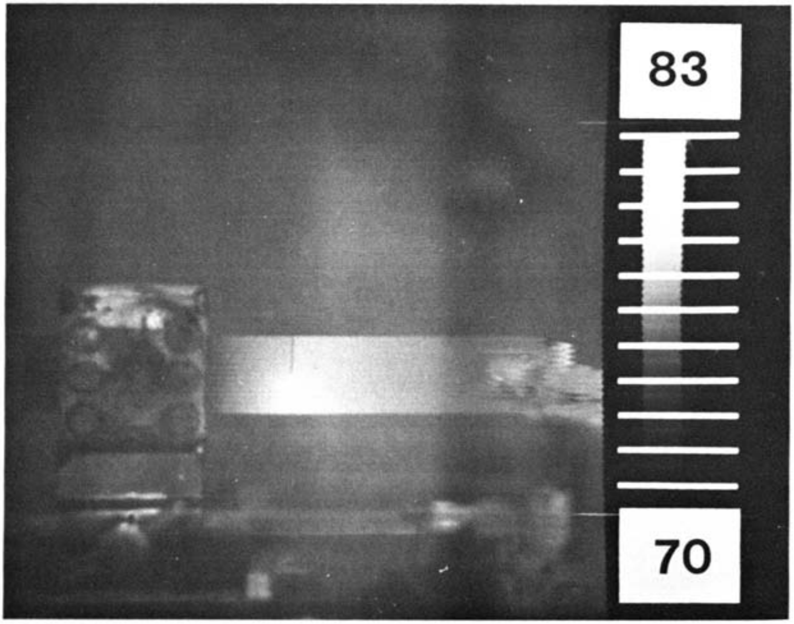

FIGURE 4b. Steel sample at 13,300 cycles.

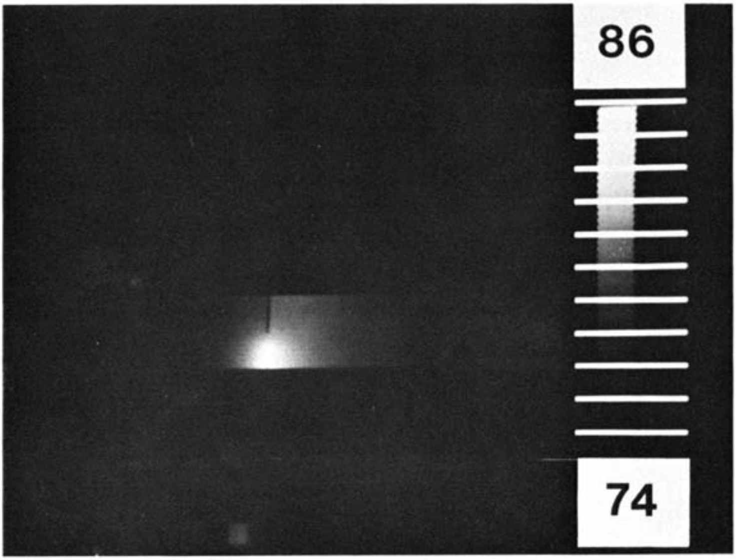

FIGURE 4c. Steel sample at 30,300 cycles.

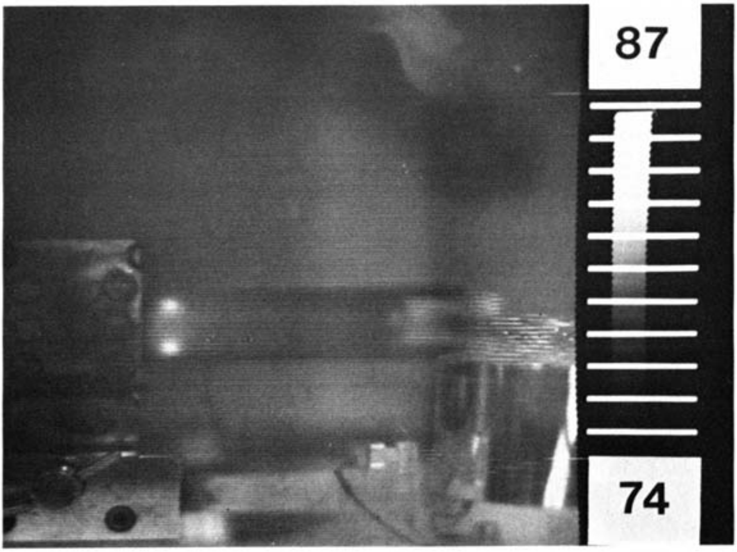

FIGURE 5a. Fiberglass sample at 28,600 cycles.

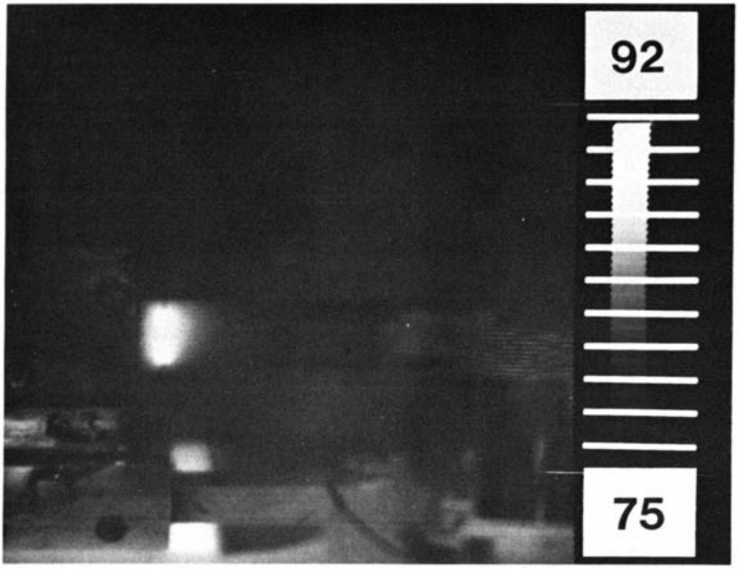

FIGURE 5b. Fiberglass sample at 109,000 cycles.

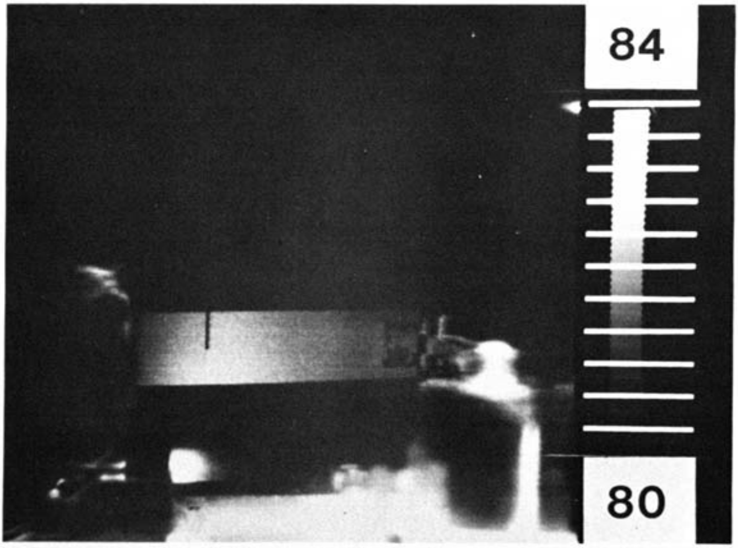

FIGURE 6. Aluminum sample at 30,000 cycles.

temperature field. The fiberglass, with a conductivity of about 0.1 Btu/hr-ft-°F, was the least efficient conductor of heat of the three samples. The temperature field in the fiberglass sample also showed the highest degree of localization about the saw cuts. The steel, with a conductivity of about 30 Btu/hr-ft-°F, displayed less localization of the temperature increase around the stress concentrations. This effect is due mainly to the increased efficiency in conducting the heat away from the region of high stress through the steel sample. Aluminum is a much more efficient conductor of heat; it has a thermal conductivity of the order of 80 Btu/hr-ft-°F. Thus the temperature distribution on the surface of the aluminum sample was rather smeared compared to that of the steel or fiberglass. So efficient is the removal of heat from the region of highest stress in the aluminum sample that it becomes difficult to locate that region in the thermogram of Figure 6.

One can conclude from the comparison of the three samples that the thermal conductivity of the material in question strongly affects the resulting temperature distribution on the surface of the sample. It may be possible to achieve a more localized temperature rise in the aluminum by altering the geometry of the samples to be fatigued. In particular, reducing the thickness further would reduce the cross-sectional area through which the heat must be transfered in conduction. By decreasing the efficiency of the conduction heat transfer the temperature distribution should become more localized. Another possible means of localizing the temperature increase in a sample is to blow air over the sample, thereby increasing the convective heat transfer from the sample. These techniques used with any material may improve the localization of the temperature rise due to fatigue damage.

The use of the scanning infrared camera in fatigue studies allows one to observe regions of high stress and fatigue damage much earlier in the sample life than is possible by visual inspection. The steel sample of Figure 4 showed definite heating at only 1800 cycles. This heating was localized about the edge of the saw cut, where it is known that the stress was highest and the fatigue damage most likely to occur. The sample displayed no visual signs of a crack until some 18,000 cycles later in its life. Thus, thermography foretold the location of the critical fatigue damage in about 10% of the time necessary to observe any damage visually. The fiberglass sample did not fail completely as did the steel, but very early in the test of the fiberglass it became apparent where the fatigue damage was going to occur. This prediction was borne out by visually observing the spots of damage to the epoxy matrix, which were, of course, centered around the ends of the two saw cuts. Owing to smearing of temperature distribution on the aluminum sample it was difficult to predict the location of the most likely fatigue damage. This problem may be solvable by using the previously discussed techniques.

CONCLUSIONS

One can conclude from the results presented in this study that thermography may be used successfully to observe the local heating associated with fatigue damage in various materials. Furthermore, this local heating is apparent long before any visual evidence of fatigue damage appears. Thus, it may be possible to use thermography as an early warning system of impending fatigue damage in materials in service. Such a use would be desirable to prevent in-service failures of mechanical devices due to the fatiguing effects of cyclic stresses.

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