NDT OF COMPOSITES BY THERMOGRAPHY

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ABSTRACT

This paper describes ongoing research efforts to evaluate thermographic techniques for locating flaws or damage in structural fiber composite laminates. An infra-red camera with video isotherm readout is used to identify perturbations in uniform or linear thermal fields which may be caused by presence of flaws or damage such as matrix cracks, delaminations, blind side impact damage, and partial through holes. This procedure has potential for rapid qualitative screening of large surface areas. Potential defective areas may then be analyzed by a more accurate (but more time consuming) method .

Two techniques are discussed; externally applied thermal field (EATF) and stress-generated thermal field (SGTF). The EATF technique involves applying heat to a composite structure and observing the resulting transient thermal pattern. The SGTF technique requires stress cycling to create hot spots in regions of high stress concentrations adjacent to flaws or damage sites.

INTRODUCTION

NDE of composite structures in either manufacturing or routine service modes can be an extensive and time-consuming operation by current techniques of ultrasonics, X- or N-rays, etc. Thermographic techniques may have possibilites for rapid screening of large surface areas; suspected small flawed regions may then be quantitatively investigated by a more sophisticated method.

For the past decade or so, many investigators have used various forms of thermograpny to locate defect or flaws in composite or other structures. The thermographic methods used fall into two categories: Externally applied thermal field (EATF) technique uses a heat source outside the structure (Figs. 1 and 2) to generate transient thermal patterns. Perturbations in the thermal patterns are read by infrared detectors (sensors, cameras, or liquid crystals) and indicate the presence of a flaw or damage (Fig. 2). The stress-generated thermal field (SGTF) technique uses the viscoelastic nature of composite matrix resins to generate heat under cyclic loading. Regions of stress concentration (near flaws or damage) will produce hot spots which can readily be observed by an IR camera (Fig. 3).

The camera used to measure the thermal fields was an AGA Themovision System 680/102 B infrared camera with both black and white and color isotherm video readouts. The black and white screen indicates surface temperature in a continuous shade of gray from black (coldest) to white (hottest). The color isotherm screen is divided into 10 distinct colors representing ten temperatures between black (coldest) to white (hottest). (In the figures of this report they appear as distinct shades of gray.) The sensitivity of the camera can be changed from 1°C (black to white) to 1000°C (black to white). Best results were obtained using the 1° through 5°C sensitivities.

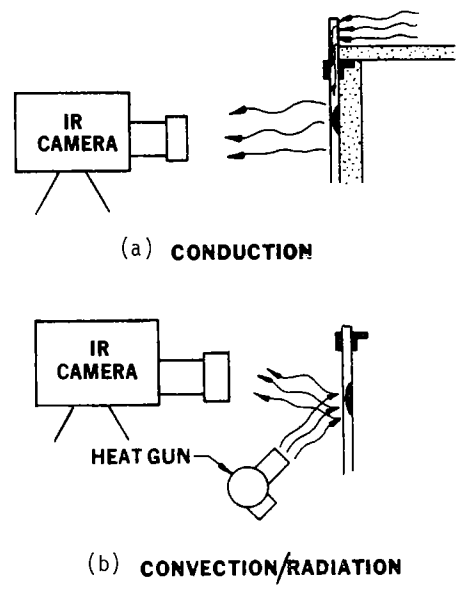


Fig. 1 Schematic diagram of externally applied thermal field (EATF) test setups.

Neither EATF nor SGTF techniques have undergone extensive evaluation for use in detecting flaws or damage in composite structures, although considerable work has been done using thermography to track fatigue crack growth (see refs. 1-3 for example). The purpose of the present program, now ending the first phase of a three phase effort, is as follows:

1. Demonstrate the feasibility of NDE by EATF and SGTF thermographic techniques.
2. Determine the capabilities and limitations of thermography for detecting delaminations, surface cracks, blind-side impact damage in com-

posites - identify ranges of flaw types, sizes, locations, types of materials, etc., for which thermography is effective.

3. Develop methods for EATF heat input and SGTF stress application that best provide for easy flaw identification.
4. Recommend hardware features for large scale usage.

Results obtained to date in the program are presented in this paper by heat application technique and flaw type. Tentative conclusions follow.

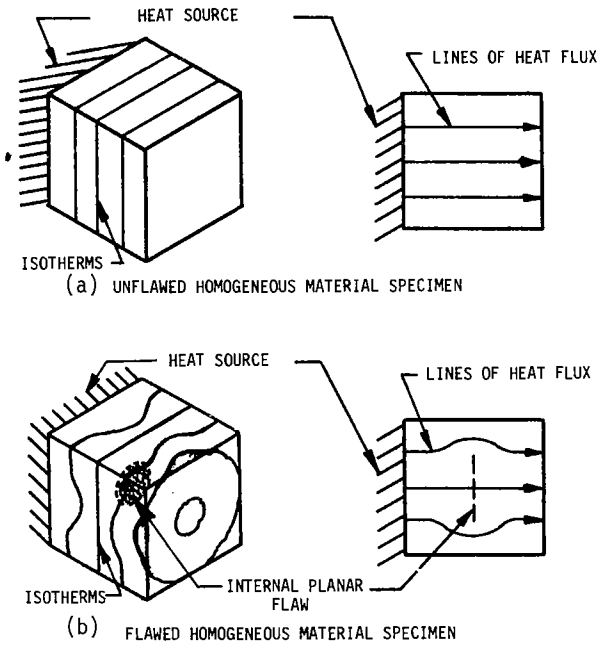


Fig. 2 Temperature fields in flawed and unflawed material with and without internal flaws, EATF.

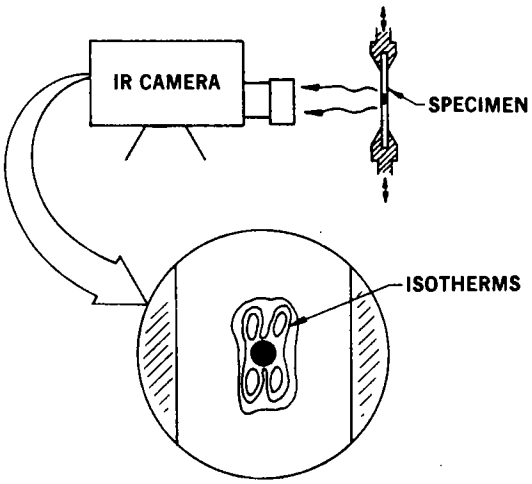


Fig. 3 Stress generated thermal field (SGTF) test setup.

EXTERNALLY APPLIED THERMAL FIELD (EATF)

Two types of EATF heat generation techniques have been studied. The first is application of heat by a strip heater or other source away from the flaw area to be evaluated (Fig. 1a). Heat is conducted in the plane of the material in a direction parallel to the surface, and is called "conduction" method for short. The second is heat application by a convection or radiation source such as a heat gun, space heater, or IR lamp, perpendicular to the surface of the specimen (Fig. 1b). This second method, for convenience, is termed "radiation/convection".

Conduction Method

Four types of flaws were investigated by the conduction method - through holes (to evaluate the effects of material conductivity and anisotropy), partial through holes (simulating blind-side impact damage), delaminations, and surface cracks.

Through holes - Through holes (Fig. 4) obviously do not need any technique other than visual inspection to find. However, 0.64 cm. dia holes were drilled through [0] graphite/epoxy, [0/90] glass/epoxy, and [0] boron/epoxy to evaluate effects of material thermal conductivity and anisotropy. Because conductivity of graphite fibers is high, and epoxy is low, [0] Gr/Ep composites have high fiber direction conductivity and low conductivity transverse to fibers. Isotherm video pictures of the effects of heat conduction parallel to fibers, perpendicular to fibers, and at 45 deg. to fibers respectively, are shown in Fig. 5. Note that large perturbations occur in the parallel and 45 deg. to fiber directions, but small perturbations in the perpendicular to fiber direction. Glass/epoxy is nearly isotropic in thermal conductivity because glass and epoxy conductivities are the same order of magnitude (and it is noted, close to that of transverse graphite/epoxy). The [0/90] glass/epoxy results are similar to [0] graphite/epoxy results in the transverse direction (see bottom left, Fig. 5). Boron conductivity is between that of glass and graphite. Boron/epoxy results are shown bottom middle and right of Fig. 5.

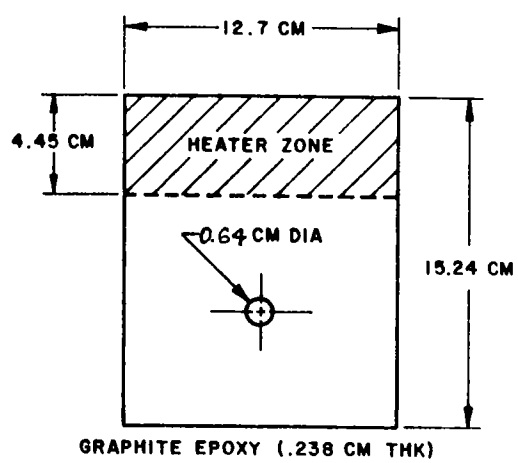


Fig. 4 Graphite/epoxy through-hole specimen.

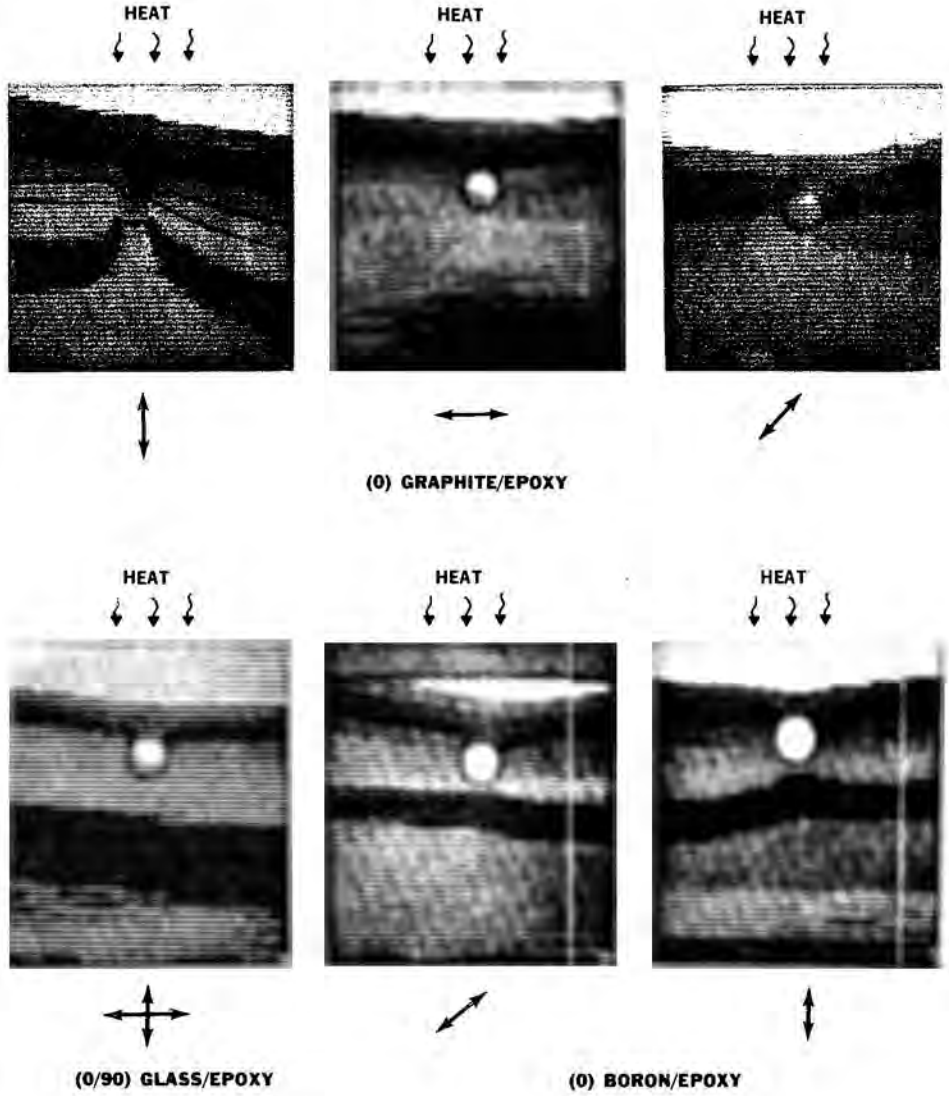
Partial through holes (simulated impact damage) - Figure 6 shows a graphite/epoxy sample with a flat-bottomed hole drilled about half-way through the back surface, simulating the back-surface shattering of moderate velocity impact damage. Figure 7 shows conduction test results on the [0] Gr/Ep sample. Note that the blind hole causes some identifiable perturbations in the otherwise straight isotherms near the center of the specimen, in spite of the fact that the hole is on the opposite side of the specimen.

Delamination - Two types of delamination were tested by conduction: an induced edge split in [0] Gr/Ep (Fig. 8) and implanted delaminations (mylar-encapsulated glass microspheres) one quarter to one inch square located one to four plies from the surface in [0/±45/90] Gr/Ep (Fig. 9). Note that isotherm perturbations locate the delaminations. Analytical heat transfer calculations (Fig. 10) indicate that a one inch square delamination can be detected in the middle of a 32 ply [0/±45/90] specimen. Glass/epoxy delamination tests are underway, and it is expected that they will more readily be observable in glass/epoxy than graphite/epoxy.

Surface cracks - Heat conducted in a direction perpendicular to surface cracks shows a steep gradient or jump right next to the crack (Fig. 11). On the right, a previously undetected crack from a partial through hole is shown by "kinks" in otherwise smoothly curving isotherms; on the left, the crack at the side of an edge split is highlighted by a 2.5°C jump in temperature.

Radiation/Convection Method

Partial through holes and delaminations in graphite/epoxy were heated by a 350 watt heat gun, and photographs of the resulting infrared camera isotherm pictures were examined.



NOTE: Arrows under plates indicate fiber directions. Heat conducted from top of specimens.

Fig. 5 Perturbed isotherm patterns around ¼-inch-diameter (0.63 cm) through-hole in composite plates, EATF.

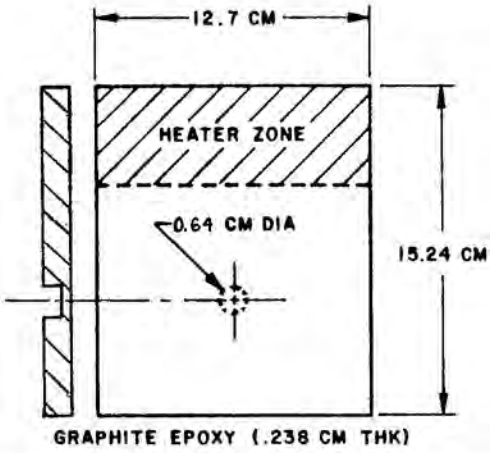


Fig. 6 Specimen with partial through hole in back surface.

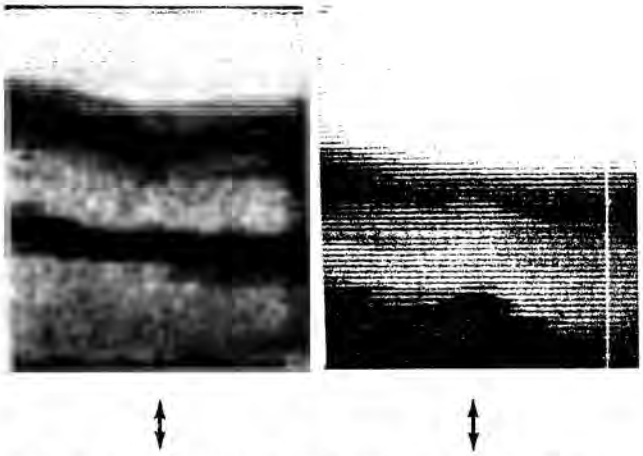
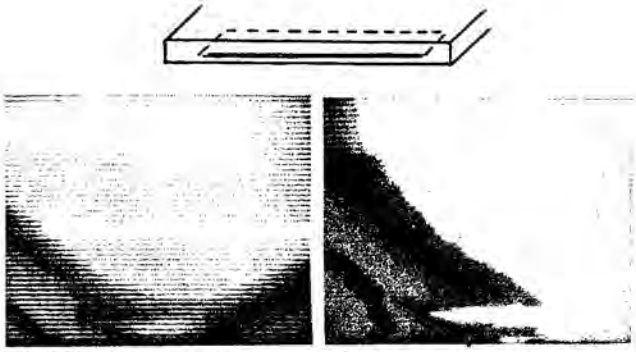


Fig. 7 Graphite/epoxy with partial through hole heat conducted from top edge.



(a) Heated from top (b) Heated from right

Fig. 8 EATF conduction results for edge delamination in [0] Gr/Ep.

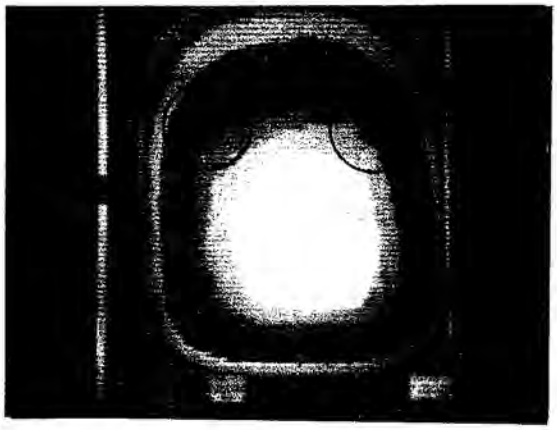
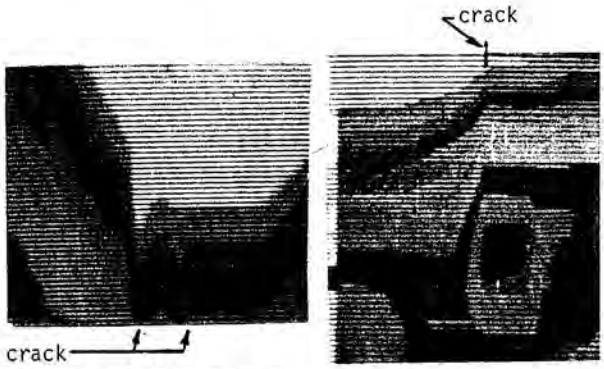


Fig. 9 [0/±45/90] Gr/Ep 8 ply sample with ¼" - 1" delams, 1 to 4 plies down from surface.

190.5	190.6	190.7	190.6	190.5
190.6	190.9	191.4	190.9	190.6
190.7	191.4	193.2	191.4	190.7
190.6	190.9	191.4	190.9	190.6
190.5	190.6	190.7	190.6	190.5

1 IN.

Fig 10 Front surface temperature distribution due to delamination 16 plies deep in 32 ply sample of Gr/Ep.



(a) Vertical edge splits (b) Vertical crack

Fig. 11 Surface cracks in Gr/Ep.

Partial through-hole (simulated impact damage) - Figure 12 shows results of heating (left) and cooling (right) the front surface of a [0] Gr/Ep sample with a 0.64 cm dia. back-surface partial through hole. In both cases, a well-defined hot (or cool) spot is produced, giving clear indication of the location and size of the flaw. Note that it is much easier to identify the hot spot from the radiation/convection method than the perturbed isotherms from the conduction method (Fig. 7).

Delaminations - Three different types of delaminations (edge split-Fig. 13, top left, edge delamination-Fig. 13, top right, and implanted mylar-glass microsphere delaminations-Fig. 13, bottom) were tested in Gr/Ep composites. The shapes and locations of the flaws are clearly defined, even in the case of free convection cooling of the surface, Fig. 13, bottom left.

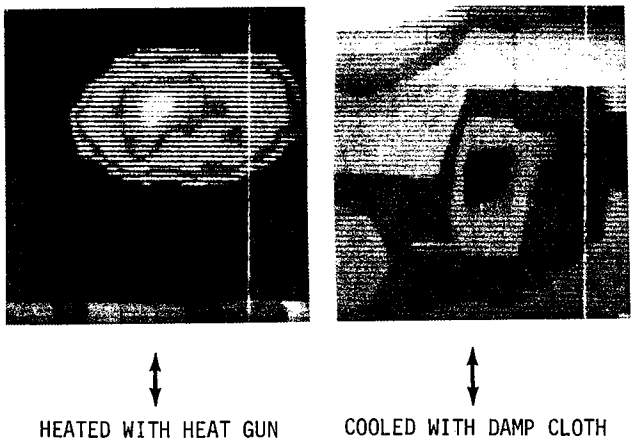


Fig. 12 Hot and cold spots at partial through-hole on back surface, [0] Gr/Ep.

Effects of Material Conductivity and Applied Heat

In the conduction method, results have shown that high conductivities are required in the direction of intended heat flux. This will insure that a temperature gradient extends along a large enough length of sample to allow detectable perturbed isotherms to form in the flaw vicinity, and will provide a reasonably sized area to be tested. Figure 14 schematically shows that the extent of the thermal gradient will be much larger in aluminum, graphite aluminum, and graphite/epoxy parallel to fiber direction than it will for glass/epoxy (any direction) or graphite/epoxy perpendicular to fiber direction.

The size of applied heat source to achieve significant temperature gradients by conduction in unidirectional graphite/epoxy parallel to fibers is shown in Fig. 15. These analytical calculations agree well with test results, and show that increasing heat input by a factor of ten does not even double the length of composite over which significant temperature gradients are obtained; and in fact indicate an asymptotic limit of about X/L = 0.7. Results of Fig. 14 show that lengths will be considerably less for Gr/Ep perpendicular to fibers and glass/epoxy. Large surface areas will therefore be difficult to examine rapidly by the conduction method. Except for surface crack detection, it appears that radiation/convection is the better method for reasons of both speed and ease of detection.

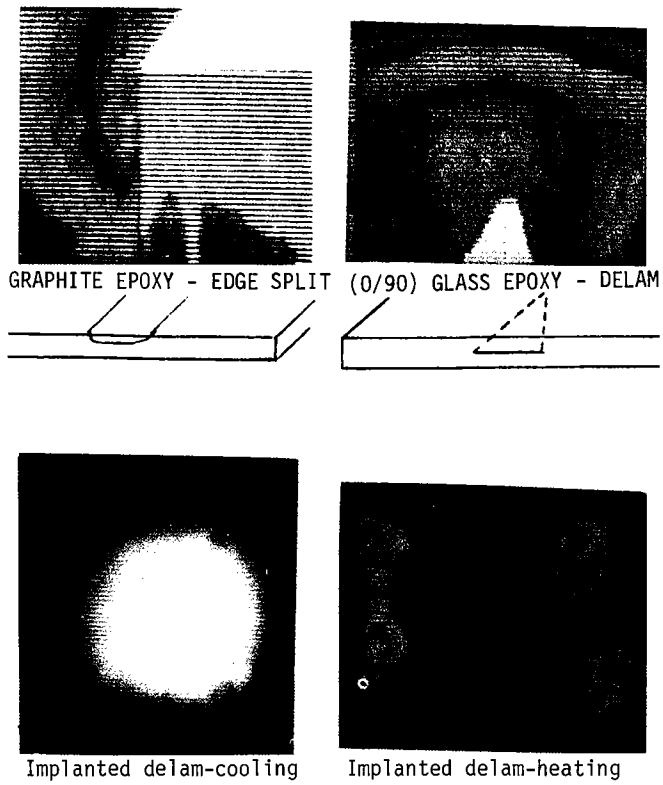


Fig. 13 Radiation/convection EATF detection of delaminations.

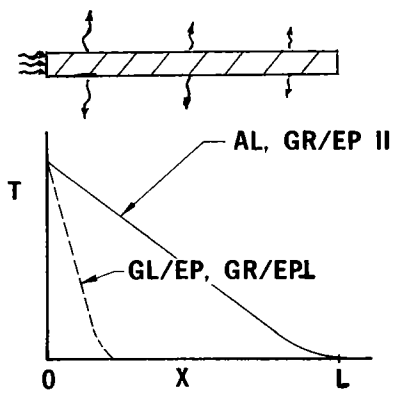


Fig. 14 Temperature (T) vs. Length (X) along wide plate heated at X=0.

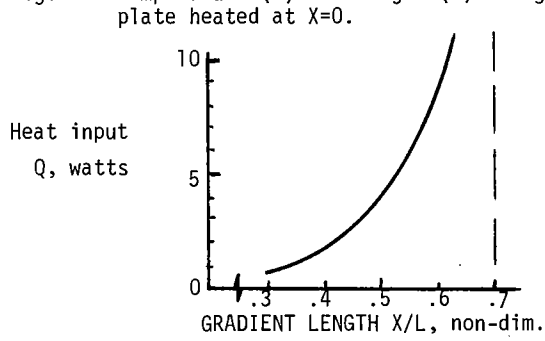


Fig. 15 Heat required to obtain temperature gradient of 0.8°C/cm vs. extent of gradient.

STRESS GENERATED THERMAL FIELD (SGTF)

In using a stress-generated thermal field to locate defects or damage, one must know the load amplitude and the cyclic frequency which will produce desired hot spots and still not damage the structure (a technique for flaw location that reduces either strength or lifetime is hardly nondestructive). Previous research (refs. 1-3) has shown that significant heat can be generated at crack tips or near holes at as low as 0.5 of static ultimate in the 20-50 Hz range of frequency for graphite/epoxy. Henneke et al. (ref. 4) have demonstrated that delaminations can be detected at ultrasonic frequencies with negligible load amplitudes. Figure 16 (upper left) shows that hot spots can be seen near a partial through-hole at as low as 0.1 of static ultimate and one Hz; but that graphite/epoxy (Fig. 16, lower left) exhibits no detectable heat at 0.3 of static ultimate and one Hz. After axial cracks developed in graphite/epoxy samples, however, the rubbing of surfaces generated considerable detectable heat, even at very low load levels (Fig. 16, right).

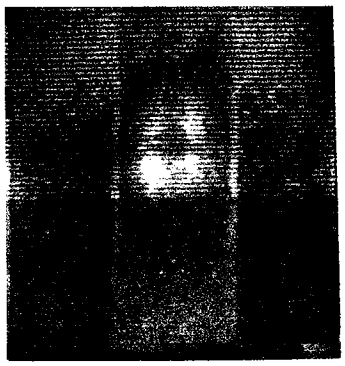
It is obvious that for flaws other than cracks which produce frictional heat, considerably higher cyclic frequencies than the 50 Hz will be required so that peak loads may be kept below levels which could cause failure. Research is in progress to develop the load-frequency relationship required to provide adequate heat for SGTF thermographic NDE.

SURFACE CHARACTERISTICS

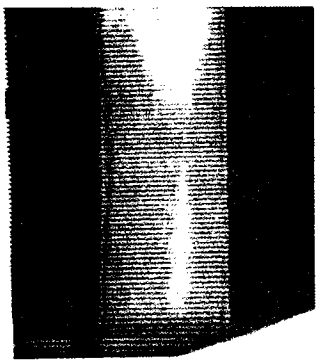
Since thermography relies upon surface infrared radiation detection, reflection from outside energy sources such as sun, lights, or body heat may give undesired signals. Also, soil, abrasions, or different paints may change the emissivity of the surface and cause spurious readings from the IR camera.

Reflectivity

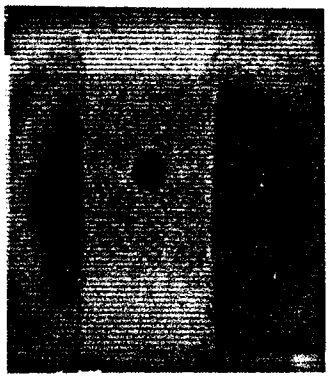
Reflections from body heat and metal objects from unpainted aluminum surfaces are shown in Fig. 17. Reflections from shiny graphite/epoxy samples are similar. To test reflectivity of flat paints, an aluminum sample was painted half flat black, half flat white (Fig. 18a). No reflection of body heat was discernable. When shiny polymeric Naval Aviation paint was tested, however, considerable reflection was obtained from a 60 watt heat source located 1.2 m from the specimen (Fig. 18b). Results show that care must be taken to eliminate sources of



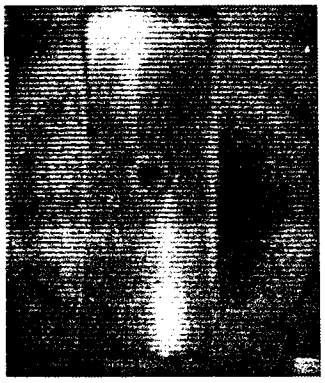
(0/90) GLASS EPOXY
1/4" PARTIAL THROUGH-HOLE



(0) GRAPHITE EPOXY AFTER AXIAL CRACKING FROM 1/4" PARTIAL THROUGH-SLIT



BEFORE AXIAL SPLIT



AFTER AXIAL SPLIT AT 0.3 STATIC ULTIMATE LOAD

(0) GRAPHITE EPOXY WITH 1/4" HOLE

Fig. 16 Stress-generated thermal fields (SGTF)at R = 0.1, 1 Hz.

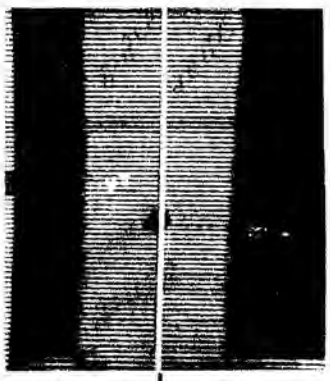
FINGER REFLECTION
WITH ISOTHERMS

FINGER REFLECTION
WITH GRAY SCALE

CAR KEY REFLECTION
WITH ISOTHERMS

CAR KEY REFLECTION
WITH GRAY SCALE

Fig. 17 Heat reflected from unpainted surface of 6061-T6 aluminum specimens.



BLACK | WHITE

(a) Flat paint (no reflection)

(b) White polymeric Naval Aviation paint (considerable reflection). Similar results with black, orange.

Fig. 18 Attempted IR reflection of heat sources from painted samples.

heat reflection such as lights, sun, etc., in orde to cut down on spurious readings.

Emissivity

Different materials radiate infrared waves at different levels. Emissivity is a measure of a surface's ability to radiate such waves. If a surface has varying emissivity from point-to-point even though it is at constant temperature, it will cause variations in radiation seen by the IR camera that could be taken for flaws by a technician. Figure 19a shows flat black and flat white paints on aluminum where heat is being conducted from the top. Note that there is no difference between the two paint colors, indicating identical emissivity. Naval Aviation paint, on the other hand, exhibits significant differences in emissivity between white and orange (Fig. 19b), and white and black (Fig. 19c). White is on the right in all pictures - samples were heated uniformly. Variations in heat emitted within a given paint sample are discussed below.

Other Surface Phenomena

In Figs. 19b and c, horizontal "streaking" can be seen in the infrared display for supposedly uniform samples of black, orange, and white Naval Aviation paint. Upon investigation, it was found that this nonuniformity is due to variations in paint thickness. The aluminum plates of high conductivity are covered with polymeric paint of low conductivity which acts as an insulator. Paint thickness variations show up as temperature variations on the heated sample's surface. Figure 20 shows this effect on a heated sample with white paint over the entire surface. The only non-uniformities in the sample are the paint thickness variations. At present, it is thought that paint thickness variations will have less effect on materials such as fiber reinforced epoxy composites, because thermal conductivities of paint and structural composites are the same order of magnitude. Samples are being prepared to test this hypothesis.

Abrasions on surfaces can also affect results. Figure 21 shows an infrared black/white photograph of a graphite/epoxy laminated plate whose surface is polished except for four areas which are rough (as if sanded). The picture was taken in complete darkness and the surface was completely uniform in temperature. The rough areas are light and the polished portions of the plate are darker, indicating that abrasions can also give thermographic readings which could be interpreted as flaws or defects.

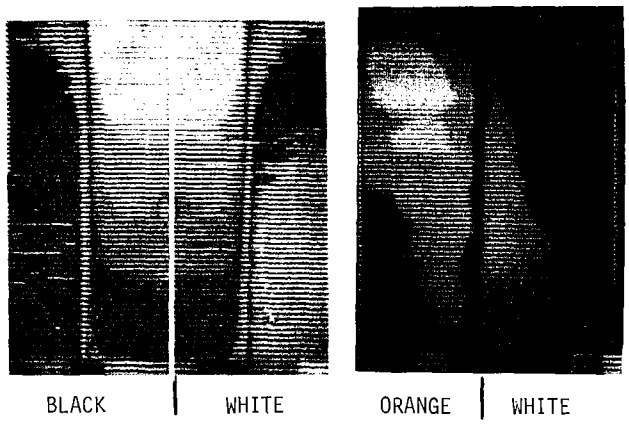
HARDWARE CONSIDERATIONS

Tests run to date have led to the following conclusions concerning the type of equipment which will be necessary to perform NDE by thermography:

Black, gray, and white isotherm video readout will be as effective in visualizing defects as color isotherms.

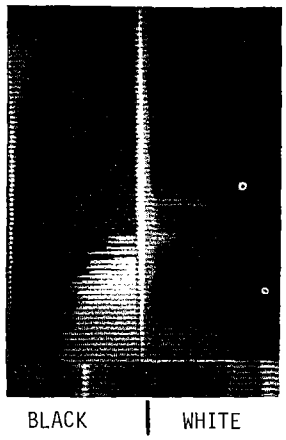
Full-scale sensitivity ranges between 1°C and 5°C work best for the flaws and materials tested. Variable positioning of these ranges on the absolute temperature scale is necessary in order to be able to adjust for differing ambient temperatures.

Even for the conduction method of heat application, a radiative heat source has found to be better than strip heaters or thermal blankets for reasons of portability and flexibility.



(a) Flat paint (no difference).

(b) Naval Aviation paint (2°C equiv. difference).



(c) Naval Aviation paint (2°C equiv. difference).

Fig. 19 Paint emissivity differences (uniform temp).

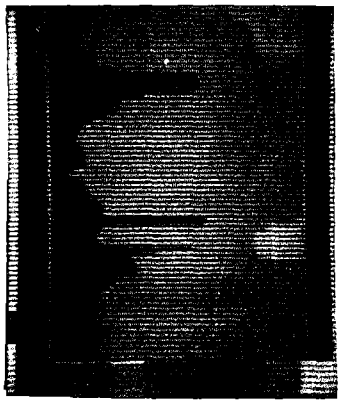


Fig. 20 IR radiation difference from uniform temperature aluminum sample painted completely white showing paint thickness variations.

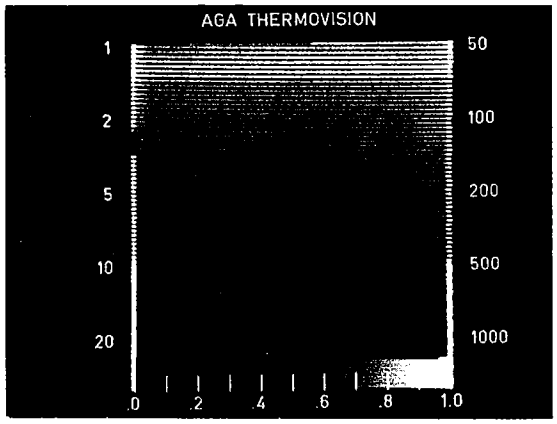


Fig. 21 Rough surface abrasions on polished Gr/Ep surface, constant temp., no reflections.

CONCLUSIONS

The following conclusions have been reached concerning EATF and SGTF thermographic NDE of composites.

The feasibility of locating delaminations, impact damage, and surface cracks in composites by thermography has been demonstrated. It appears that there will be limits on sizes and locations of the various types of flaws which can be detected, and these limits will be dependent upon heat source type and size (EATF), cyclic load level and frequency (SGTF), specimen thickness, and material conductivity. A large radiative heat source capable of causing transient surface thermal conditions will probably be required to obtain optimum flaw detection capability.

Surface characteristics (paint type, emissivity, reflectivity, soil, abrasions) are critical to accuracy of results. Surfaces to be tested must be shielded from background energy inputs such as sun, lights, and engine exhausts.

Additional details of the research performed and some results for aluminum structures can be found in references 5-7.

ACKNOWLEDGEMENTS

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REFERENCES

1. Reifsnider, K. L., and Stinchcomb, W. W., "New Methods of Mechanical Materials Testing Using Thermography", Proceedings, Infrared Information Exchange, 1976.

2. Whitcomb, J. D., "Thermographic Measurement of Fatigue Damage", NASA Technical Memorandum 78693, May 1978.

3. Charles, J. A., "Liquid Crystals for Flaw Detection in Composites", ASTM Committee D-30 Conference on NDE and Flaw Criticality for Composite Materials, Philadelphia, 10-11 Oct. 1978.

4. Henneke, E. G., II, Reifsnider, K. L., and Stinchcomb, W. W., "NDE of Composites by Vibrothermography", Review of Progress in Quantitative NDE, DARPA/AF, July 14-18, 1980.

5. McLaughlin, P. V., Jr., McAssey, E. V., Jr., and Deitrich, R. C., "Aerostructure Nondestructive Evaluation by Thermal Field Techniques", Report NAEC-92-131, Naval Air Engineering Center, Lakehurst, NJ, November, 1979.

6. McLaughlin, P. V., Jr., McAssey, E. V., Jr., and Deitrich, R. C., "Non-Destructive Examination of Fiber Composite Structures by Thermal Field Techniques", NDT International, Volume 13, April, 1980, pp. 56-62.

7. McAssey, E. V., Jr., McLaughlin, P. V., Jr., Koert, D. N., and Deitrich, R. C., "Thermographic NDT of Composites Using Externally Applied Thermal Fields", Proceedings, 35th Annual Conference, Reinforced Plastics/Composites Institute, S.P.I., February, 1980, pp. 26A 1-8.