Chapter 15
Detection of Early Stage Material Damage Using Thermophysical Properties

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Abstract This paper presents a preliminary study on the effects of fatigue induced microstructural damage on the thermophysical properties of carbon fiber polymer composites commonly used for aerospace applications. The goal is to identify thermal properties that may serve as viable indicators of early stage material damage during structural health monitoring (SHM). A series of fatigue tests were conducted on multilayer composite specimens with peak stress $\sigma_{max} = 0.55\sigma_u$ (the static strength) and stress ratio R = 0.1. The cyclic load was paused periodically at predefined cycle intervals starting from 100 cycles through end of test at 150 k cycles. At each pause, the front side of the specimen is instantaneously heated with a high intensity flash followed by temperature measurements by two thermocouples attached at the front and back sides the rectangular specimen. Simultaneously, IR images are recorded using high speed camera. Changes in thermophysical properties including heat transfer rate (Q), thermal conductivity (k), heat capacity (c) were computed as functions of fatigue cycles. Preliminary data shows that the time-temperature (T-t) evolution is correlated to the number of fatigue cycles or consumed fatigue life of the specimens.

Keywords Thermography • Early stage composite damage • Fatigue • Structural health monitoring • Microcrack

15.1 Introduction

Until most recently, composite materials were considered as fatigue insensitive and less prone to fatigue damage. One of the reasons implied behind this statement was that the conventional loading levels applied to composite systems were far too low to initiate any local damage that could induce failure under repeated loading [1, 2]. As such, the requirement for no growth of defects has always been assumed to be sufficient for the design of composite airframes. However, with the continuous improvement of composite manufacturing methods during the last decades and the requirements on structural weight reduction for future air platforms means that composite structures are subjected to loads increasingly closer to their ultimate static strength [3]. Such increase in operational loads by reducing the capacity margin down to a minimum is likely to lead to situations where series fatigue damage develop. To date, there are no theoretical predictive or simulation models to reliable describe the mechanics of cumulative fatigue damage in composites [4, 5]. Hence structural state awareness, diagnostics, and life predictions are primarily data-driven, carried out using structural health monitoring (SHM) sensors such as ultrasonic pitch-catch, pulse-echo, optical FBG, strain gages, and acoustic emission sensors. Existing structural health monitoring sensors however are only reliable for detecting large or macroscale damages (such as large crack, delamination or debond). For critical airframe structures, information on macroscale damage will not provide sufficient warning time for corrective actions. Hence there is a continued search for reliable early stage damage detection techniques in composite airframe structures and systems.

Thermophysical properties of solids, such as thermal conductivity, transmittance, diffusivity and the kinetics of interaction and energy exchange among the principal carriers are based on microscopic (or atomic) level material configuration and interaction. Changes in microscopic material state (or configuration) due to stress concentration, shear localization, adiabatic shear bands, crazing, and dislocation, that typically appear in the early stage of fatigue damage, may be correlated to changes in the thermophysical properties. A thorough investigation into the correlation of thermophysical properties of composite with progressive fatigue damage in terms of microscopic states (crazes, dislocation), however, has not been performed yet. There is evidence, nonetheless, that thermal discontinuities occur due to microscopic defects induced by cyclic loading. Figure 15.1 shows the connection between early stage fatigue damage and its effect on the thermal properties of the

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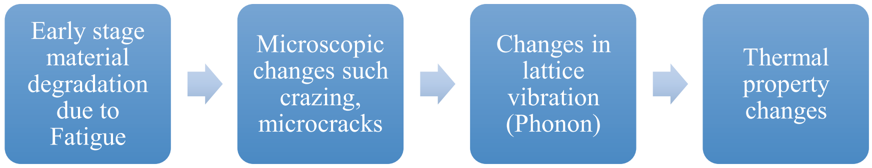

Fig. 15.1 Changes in microscopic material state (or configuration) due to stress concentration, shear localization, adiabatic shear bands, crazing, dislocation that typically appear in the early stage of fatigue damage, may be correlated to changes in the thermophysical properties

constituent materials. Hence the focus of this study is to investigate the relations between early stage fatigue damage, the ensuing internal microscopic degradation, and the changes thermal properties of composite materials. The main emphasis is on the relationship between variations in the heat transfer rate and fatigue cycles N.

15.2 Theory

The material property of a composite depends on properties of the fiber and matrix, the volume fraction, and the interfacial property. The fibers impart most of the strength and stiffness to the composite while the matrix transfers the external load to the fiber through interfacial bonding. The reliability of a composite structure as a whole depends primarily on the integrity of the interfacial bonding between the matrix and fibers and how well the load is being transferred. Almost always early stage fatigue damage starts at the interface and precedes all other modes of failure. It doesn't result in the final failure of the composite, but does contribute to strength/stiffness degradation in the laminate. Once an interfacial damage appears it gradually spreads through the entire width of the laminate.

Much like the mechanical strength and/or stiffness, the quality of the interface also affects the heat transfer property of the composite mainly in the transverse direction (perpendicular to fibers). Since carbon fibers have excellent longitudinal (axial) conductivity the interface is not critical to longitudinal heat transfer. In the transverse direction, however heat flux must cross the fiber-matrix interface repeatedly. Therefore, any change in the interfacial integrity will have a major effect on the transverse thermal properties such as thermal conductivity, transmittance and heat transfer rate.

Heat-transfer effects include thermal conduction, radiation, and convection in which the heat passes through the material to make the temperature uniform in the specimen. Temperature distribution in general carries useful information about the structural material property. Studies have shown that the thermal conductivity, k, may be used for measuring the degree of anisotropy in load bearing structures [6]. Variations in thermal conductivity may arise as a result of local inhomogeneity or flaws in the material [7]. In general, the thermal behavior of a solid is governed not only by its thermal conductivity but also by its heat capacity, c. The ratio of these two properties is termed as the thermal diffusivity, $\alpha = k/c$, which is often the governing parameter for unsteady state heat transfer. A high value of the thermal diffusivity implies a capability for rapid and considerable changes in temperature.

As stated earlier, the focus of this study is to investigate the correlation of thermal properties of composites to early stage fatigue damage. Since the fiber-matrix interface is the weakest part of a laminate [8], any change in the observed thermal property is typically assumed to be due adverse changes (degradation) in the integrity of the interface.

15.3 Experimental Setup

The experimental phase of the study presented here uses pulsed thermography shown in Fig. 15.2 to monitor the temperature-time (T-t) evolution and the heat transfer rate through the carbon epoxy test specimen. In pulsed thermography, the surface of a specimen is heated with a brief (typically, a few milliseconds), spatially uniform pulse of light from a xenon flash lamp source. An IR camera interfaced to a PC monitors the time dependent response of the specimen surface temperature to the thermal impulse. Typically in areas of the specimen surface closest to a thermal discontinuity (e.g. a wall, layer boundary or delamination, debond), the transient flow of heat from the surface into the sample bulk is wholly or partially obstructed, thus causing a transient, local temperature increase at the surface. In the test performed here, simultaneous to the IR imaging, the front and back temperatures of the specimen few millimeters away from the tip of the center hole (which is the region of maximum stress concentration) are measured using two thermocouples. The arrangement of various systems used in the test are shown in Fig. 15.2.

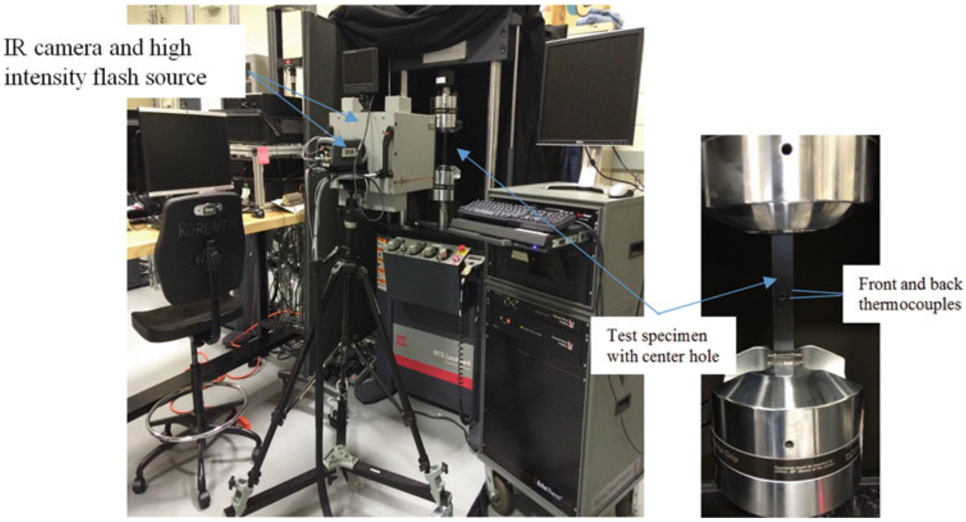

Fig. 15.2 Experimental setup showing the pulsed thermography. The test sample is a rectangular carbon-epoxy laminate with a centre (fastener) hole. Two thermocouples are attached at the front and back near the centre hole in the mode-I direction. Surface temperatures are measured after the application of the high intensity flash at the front of the specimen

The fatigue test specimen is loaded on a hydraulic servo controlled uniaxial test frame and is subjected to a tension-tension sinusoid at a frequency of 5 Hz and load ratio $\sigma_{min}/\sigma_{max} = 0.1$. The test specimen is $[(\pm45^o)_2/0^o]$s symmetric laminate with a thickens of 0.128 in (3.25 mm). The peak load of the sinusoid $P_{max} = 20$ kN.

During data acquisition, the cyclic load is paused periodically at predefined cycle intervals starting from 100 cycles through end of test at 150 k cycles. At each pause, the specimen is allowed to cool down to room temperature so as to bring the specimen to the same initial energy state during each successive pause while allowing for the dissipation of viscoelastic heating before probing the thermal properties. After the specimen is cooled to room temperature (22 °C), the front side is instantaneously heated with a high intensity flash followed by temperature measurements by two thermocouples attached at the front and back sides the rectangular specimen and IR imaging.

15.4 Results and Discussions

Figure 15.3 shows the readings of the front and back thermocouples at after the application of a high intensity flash at the given fatigue cycle. Each curve denotes the evolution of (T-t) at specific number fatigue cycles.

The plots are color mapped from blue (low cycle count) to red (high cycle count). Fig. 15.3a shows the temperature decay at the front of the specimen, Fig. 15.3b shows the transient temperature increase at the back of the specimen while Fig. 15.3c shows the relative changes in the surface temperature at the back and front of the specimen.

Immediately after the application of flash, the temperature of the front surface increase by about 4-°F. After a brief delay the temperature of at the back increases as the heat conducts through the thickness. The data shows that the (T-t) evolution is well correlated to the number of fatigue load cycles that the specimen has absorbed at any given time. Notice the clear trend of the color mapped lines with blue (low cycle) lines clearly separated from the red (high cycle) lines. As N increases, the specimen appears to lose the input energy, i.e. the external heat imparted by the flash, rather very quickly. The data from the back thermocouple shows that, the peak recorded temperature at the back of the specimen drops sharply as the fatigue cycles continue to increase. A possible explanation for this observation is as follows: the process of accumulation and development of fatigue damage is associated with crazing and microcracking, which is determined by the processes of initiation, motion, generation, and merging of point defects. The density of microcracks grows with increase of the loading cycles N. High density microcrack leads to loosening of material, primarily around the interface and in/around regions of high stress concentration in the matrix. This creates higher thermal resistance in the transverse direction where the heat is supposed to flow. The high transverse thermal resistance (created by the microcraks and loose material) forces the heat transfer possibly along the fiber direction (high thermal conductivity). A comprehensive explanation of the observed heat flux phenomena, however, is yet to be established.

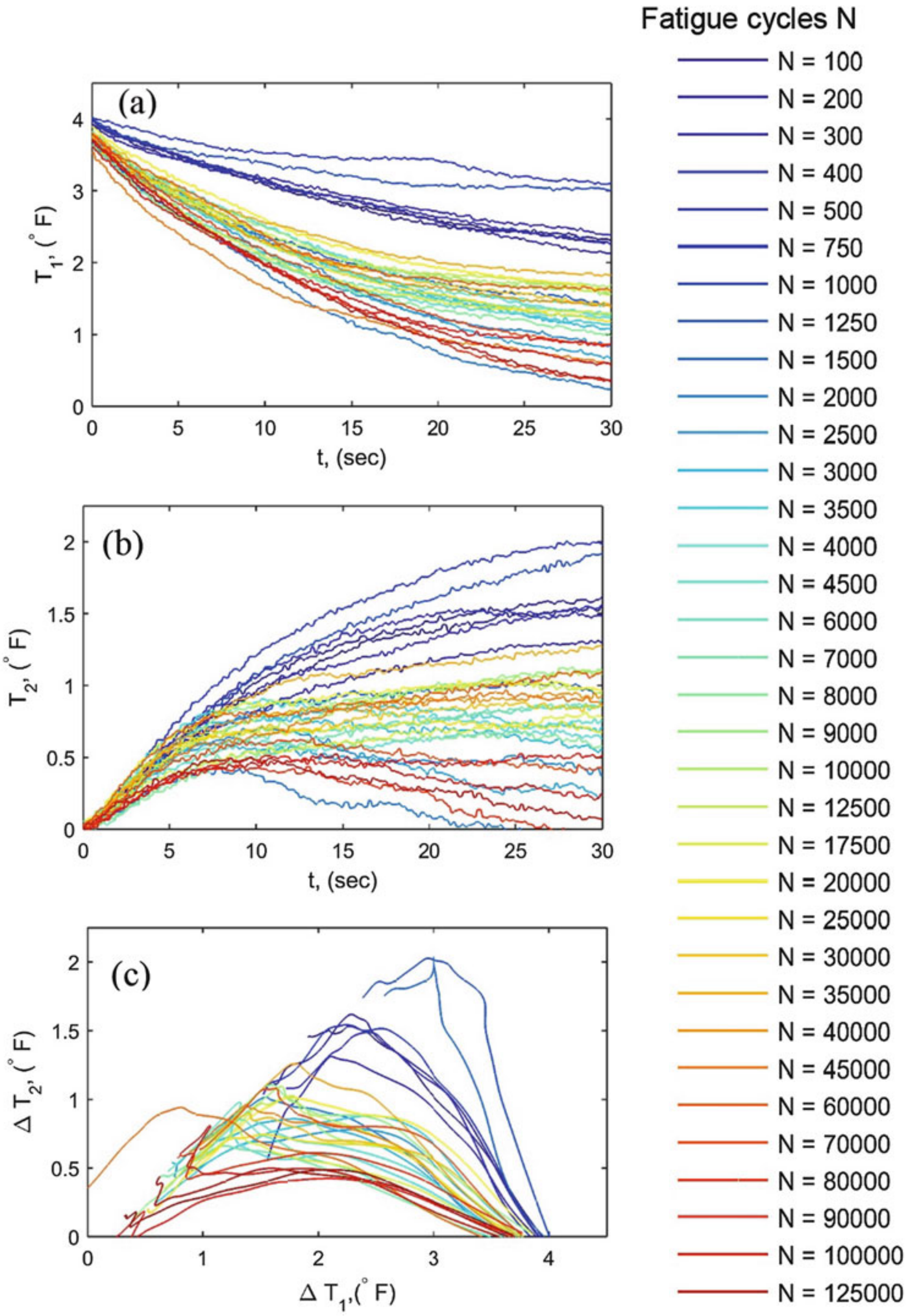

Fig. 15.3 Readings of the front (T_1) and back (T_2) thermocouples at various cycle count N at the tip of a center hole on a carbon-epoxy laminate. The plots are color mapped from *blue* (low cycle count) to *red* (high cycle count). The data shows that the heat capacity of the specimen, as well its thermal conductivity change with the number of applied fatigue cyclic. The change in thermal property may be attributed to increase in microcrack density and the loosening of material around fiber-matrix interface. (**a**) Temperature of the front surface T_1 as a function of time, (**b**) Temperature of the back surface T_2 as a function of time, (**c**) Temperature of the front surface as a function of the back surface

15.5 Conclusions

This study is primarily intended to investigate the feasibility of detecting early stage structural damage in carbon-epoxy systems, such as crazes and microcracks using changes in themophysical properties of the material. Several published work is available on the subject area of thermography for the detection of large scale damage events such as delamination, debonding or large cracks in structures. However, the work presented here, is among the first attempts to detect early stage damage in composite structure well before the appearance of large damage. The central hypothesis of the paper is that changes in microscopic material state resulting from stress concentration, shear localization, adiabatic shear bands, crazing, microcracks that typically appear in the early stage of fatigue damage, are correlated to changes in the thermophysical properties. To test the hypothesis a carbon epoxy specimen is subjected to increasing cyclic loading. The cyclic load was paused periodically at predefined cycle intervals starting from 100 cycles through end of test at 150 k cycles. At each pause, the front side of the specimen is instantaneously heated with a high intensity flash followed by temperature recordings by two thermocouples attached at the front and back sides the rectangular specimen. The data shows that the (T-t) evolution is well correlated to the number of fatigue load cycles that the specimen has absorbed (aka usage). The trending of (T-t) may be explained in terms of change in microcrack density (damage) and the ensuing change in the transverse thermal resistance and heat flow patterns. Additional tests are required to further validate the observed phenomena and verify the hypothesis. If such can be done successfully, thermal measurements may be used as a new structural health monitoring technique to estimate the extent of internal damage in the early stage of the life cycle of a components as well as provide a reliable prediction of remaining useful life of airframe components.

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