Session 2559

# DETECTING HEAT DAMAGE IN COMPOSITES USING LASER INDUCED FLUORESCENCE

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## Abstract

Polymer-matrix composites (PMCs) have acquired popularity and acceptance in the aerospace industry. Their mechanical characteristics and low weight makes them desirable for fabrication of the structural and nonstructural components. However, the PMCs suffers thermal degradation upon exposure to elevated temperatures. These thermally degraded resins experience drop in mechanical strength and are eventually damaged. Composites visual and microscopic inspection may indicate that the composite is undamaged but in actuality may have lost up to 70% of their original strength due to chemical changes resulting from heat damage.

This paper will discuss implementation and comparison of portable laser induced fluorescence system and laser induced imaging system to detect heat damage in composites. These systems were considered because conventional methods are not suitable to detect the aforementioned heat damage but are meant to detect mechanical damages such as cracks and material loss.

In an effort to understand the implementation of the techniques involved in the detection of heat damage in polymer composites, this paper will discuss the results from the previous study and this study to demonstrate that laser-induced fluorescence offers a great promise as a powerful, innovative approach for rapidly detecting incipient thermal damage in polymer. Finally, discussion on future work will be presented to refine software and hardware components to develop a robust and automated system.

## Approach

Laser-Induced Fluorescence (LIF) spectroscopy is a sensitive and powerful approach for detecting molecules and atoms, measuring species concentrations and energy-level population distributions, and for probing complex materials such as polymer composites. LIF is an attractive approach for detecting heat damage because it provides a sensitive means for detecting changes in the electronic structure and environment of polymer composites.[3]

Excellent work has been conduct by Fisher et.,al, in the past few years to detect heat damage in polymer composites. In their study, laser light exiting a multi-mode optical fiber was used to evenly illuminate the entire surface of 30 x 30-cm panels. Fluorescence was collected with a 35-mm SLR camera lens and focussed on the detector of a CCD camera. Colored glass filters mounted in front of the collection lens were used to reject scattered laser light.[4] In their study, emission spectra were collected with excitation wavelengths ranging from 325 to 785 nm, and values for peak fluorescence intensity and corresponding wavelength were determined for each coupon at each wavelength. In general, two trends were noticed in these data. First the intensity increased rapidly at the onset of heat damage and then decreased considerably from this peak upon further thermal degradation. These trends are clearly illustrated in figure 1, which presents emission spectra (excitation wavelength) of four coupons having different thermal histories.

The results reported by Fisher et. al, have demonstrated that laser-induced fluorescence offers a great promise as a powerful new approach for detecting thermal damage in polymer composites, especially at the onset of the damage. However, their study indicated some uncertainty due to the inversion in the series of images, which could be avoided by using an imaging method based on wavelength of maximum intensity. They suggested that a tunable wavelength selective filter (such as an Acousto-Optical Tunable Filter (AOTF)) could be used to replace the colored glass filter. This approach would permit automated collection of an array of images at different wavelengths that could be processed to produce an image based on wavelength shift, and therefore provide a direct approach for quantitatively determining heat damage over large area.

The following paragraphs will describe the basic system components needed for the portable laser induced fluorescence system and the laser induced fluorescence imaging system.

## Portable Laser Induced Fluorescence System Configuration

The portable laser induced fluorescence measurement concept is similar to the imaging system concept in terms of collecting the fluorescence but in case of portable system measurements are made at a single point. Portable system configuration is indicated in figure 1. The system utilizes a small laser, which is used in conjunction with a fiber optic emitting and receiving probe to illuminate the surface and gather the fluoresced light. The probe is also connected to one of the channels of an optical spectrum analyzer, which is used to determine the wavelength at which the peak fluorescence occurs.

The heart of the portable laser induced fluorescence is the spectrometer. The portable spectroscopy system is comprised of the following four basic elements:

1. A green diode laser, which is used to induce the fluorescence.
2. Sampling optics to transmit the laser light to the specimen and to collect the induced fluorescence light.

3. The spectrometer, which measures the amount of light at each wavelength in the spectrum.
4. An analog-to-digital converter, which converts the analog data from the spectrometer into digital information and passes it to a computer, whereby it can be post-processed and converted into a format that is useful to the end user.

The portable system was constructed and tested with the aid of Computer Interface Instrumentation, Inc. A reflection probe was used to test the specimen. The reflection probe used in this system consisted of an assembly of seven fibers in a ferrule. The inner (central) fiber was used to transmit the laser light to the surface, while the outer ring of six fibers was used to gather the reflected and fluoresced light and transmit it to the spectrometer. Measurements take about one second and are made by pointing the probe at the surface to be inspected from a distance of approximately 3/8”.

The spectrometer is controlled through the software developed by ocean optics. The software uses the analog-to-digital converter as the computer interface. The software supports drivers for 2 analog-to-digital converters. The ADC500 (analog-to-digital converter) samples at the rate of 500,000 samples/sec, with a 12-bit A/D system on an ISA card. This card is used to operate spectrometers with desktop PC computers. The portable system utilizes the PC1000, which is functionally equivalent to the ADC500 and uses similar drivers. Other A/D products and software can be used to control spectrometers. For example, LabVIEW drivers as well as LabVIEW applications from National Instruments can be used in the portable system. For the desktop PC running under Windows NT/98/95 following PCI cards can be incorporated in the system to interface at higher sampling rates and faster throughput.

- PCI-MIO-16E-1 (Analog-to-Digital converter, supports PCI bus with sampling rate of 1.25 MS/s and 16 analog inputs)
- PCI-6071E (Analog-to-Digital converter, supports PCI bus with sampling rate of 1.25 MS/s and 64 analog inputs)
- PCI-MIO-16E-4 (Analog-to-Digital converter, supports PCI bus with sampling rate of 500kS/s and 16 analog inputs)

For laptop or notebook computers, the DAQ700 PCMCIA card is supported. The DAQ700 card is 100kS/s 12-bit system.

Eight samples were tested with the portable laser induced fluorescence system. The following were the characteristics of samples in terms of heat exposure and time:

- No heat exposure
- 350F for 60 minutes
- 450F for 60 minutes
- 550F for 5 minutes
- 550F for 30 minutes

- 550F for 60 minutes
- 650F for 5 minutes
- 650F for 30 minutes
- 650F for 60 minutes

The results of the portable laser induced fluorescence system for the aforementioned heat damaged specimens are shown in figure 2.0. The plots have been normalized by subtracting the spectrum of the undamaged specimen. Results show the shift in wavelength, as the heat damage for composite specimens is prominent with the increase in temperature. These results are reported with some uncertainty and will be verified in future experiments. The data was collected with green laser excitation. It is suspected that the poor signal-to-noise ratio is a result of the reflected laser light not being filtered out. A high pass, in-line optical filter has been ordered and will be placed in the fiber optic line that transmits the gathered light back to the spectrometer.

Experiments conducted in this study show a considerable amount of promise to verify the results of a study conducted at the Oak Ridge National Laboratory to detect thermal damage in graphite/epoxy components based on laser induced fluorescence.

## Laser Induced Fluorescence Imaging System Configuration

The laser-induced fluorescence imaging system is derived from the previous work conducted by Fisher et., al. Results of previous work has clearly demonstrated the feasibility of using a CCD camera to monitor fluorescence intensities from panel surfaces, allowing high resolution location of damaged areas. It was recommended that the extent of thermal damage in these heat-damaged areas could be quantified by measuring the wavelength shift of this fluorescence. Based on this recommendation, current work involves analyzing the entire fluorescent spectrum and extracting images based on the wavelength at which peak fluorescence occurs.

The imaging system configuration is illustrated in figure 3.0. The imaging system consists of Argon-Ion lasers (514nm/100mW) to excite the test specimen and an AOTF with appropriate optics in front of a CCD camera to select various fluorescence bands. Hewlett Packard (HP) 8647A-signal generator was used to provide the frequency input to the AOTF to determine the wavelength. Virtual Instrument (VI) was developed to interface the HP8647A via the GPIB (General Purpose Interface Bus) to a personal computer. The interface enabled the operator to change the RF from the front panel of the VI.

The heart of the imaging system is the AOTF, which acts as an electronically tunable spectral band pass filter. The band pass wavelength is changed by varying the frequency of a radio frequency (rf) field applied to the crystal. The AOTF used in this work was purchased from Brimrose (Model TVA-100). According to the manufacturer, this AOTF has an effective wavelength range of 400nm to 1100nm. The wavelength-frequency curve for the AOTF is shown in figure 5.0.

Tests were conducted using the portable spectrometer to obtain a uniform amount of transmitted light throughout the spectrum of interest when a white light source is placed in front of the AOTF. The following table illustrates the spectrum in relation to input frequency, wavelength and amplitude.

| **Radio Frequency (RF) (Input) HP 8647A MHz** | **Wavelength (nm) AOTF** | **Amplitude (dbm) 200 CPS** |
|---|---|---|
| 150 | 516.73 | -0.7 |
| 145 | 528.17 | -2.0 |
| 140 | 542.13 | -4.0 |
| 135 | 557.49 | -6.0 |
| 130 | 574.21 | -5.5 |
| 125 | 591.91 | -5.6 |
| 120 | 611.29 | -6.6 |
| 115 | 632.66 | -7.6 |
| 110 | 655.98 | -8.1 |
| 105 | 681.88 | -7.2 |
| 100 | 710.62 | -5.1 |
| 95 | 742.44 | -1.8 @ 170 CPS |
| 90 | 778.22 | +2.0 @150 CPS |

LabView controls the process of image acquisition at aforementioned frequencies. Initially the frequency is set from the front panel and the user can click on run camera from the front panel to acquire an image at the corresponding frequency and amplitude illustrated in the above table. This process is repeated until images of all the bands of interests have been acquired and stored. The images are viewed in the LabView environment by using the IMAQ (Image Acquisition) software.

LabView is a development environment based on the graphical programming language G. LabView relies on graphical symbols rather than procedural language in describing programming actions. All LabView programs, or virtual instruments (VIs), have a front panel and a block diagram. The front panel is the graphical user interface of the LabView VI. This interface collects user input and displays program output. The block diagram contains the graphical source code of the VI. The block diagram can include functions and structures from the built in LabView VI libraries. Following paragraphs will discuss the block diagrams of the VIs used in the imaging system.

VI was developed to interface the HP8647A via the GPIB to a laptop computer. This interface allows the user to change RF and corresponding amplitude from the front panel of the VI.

**Loop and Sub VI (HP8647A)**

The wiring diagram for the VI is shown in figure 4.0. The outer loop is a For loop, this loop is executed 13 times (0 – 12). Inside the For loop is a While loop, the While loop has an iteration terminal i that counts the number of times the loop will execute. The condition terminal expects a true or false input. A true input forces the While loop to run indefinitely, and a false input terminates execution. The output of the iteration from the adder is connected to the sub VI (HP8647A) shown in figure 6.0. Amplitude for the corresponding frequency is entered in the array structure and the output of each element of the array is connected to the amplitude input of the sub VI (HP8647A).

**Results**

- A computer control software module was developed using the LabView for the AOTF.
- Laser illumination was demonstrated
- Spectrum analyzer has been tested
- Camera control software was upgraded
- Functionality of AOTF was used to determine the bandpass characteristics of the AOTF as a function of input frequency and voltage.

**Future Work**

The results reported here from the previous study and this study demonstrate that laser-induced fluorescence offers a great promise as a powerful, innovative approach for rapidly detecting incipient thermal damage in polymer. Additional research is necessary to refine and automate these processes and to relate the fluorescent spectrums to mechanical degradation. In addition, further detailed study of the basic processes producing this phenomenon and the supporting chemistry of the spectral signatures is needed to fully understand the applicability and limitations of this method. Other factors such as the effects of surrounding atmospheric conditions, age of the PMC, thermal cycling, long term exposure to temperature, and the presence of surface coatings (such as paint and primers must be evaluated to insure that changes in these variables will not degrade the utility of the method. Lastly, this method needs to be researched to determine it's utility for use as a cure monitoring tool.

**Discussions And Conclusion**

This paper presented a brief discussion of implementation and comparison of portable LASER induced fluorescence system and LASER induced imaging system to detect heat damage in composites. This project has provided a practical example of Computer based instrumentation for engineering technology students at Savannah State University, furthermore the authors would like to acknowledge ASEE and Office of Naval research for the support of this project.

## Bibliography

1. B.J. Frame, C. J. Janke, W. A. Simpson, R. E. Ziegler, and H. E. Philpot, Composite Heat Damage, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1990.
2. C. J. Janke, J. D. Muhs, E. A. Wachter, R. E. Ziegler, G. L. Powell, N. R. Smyrl, and H. E. Philpot, Composite Heat Damage Spectroscopic Analysis, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1990.
3. L. P. Robert. Applications of Laser-Induced Fluorescence Spectroscopy for Combustion and Plasma Diagnostics, Sandia National Laboratories, Livermore, California.
4. W. G. Fisher, J. M. E. Storey, S. L. Sharp, C. J. Janke, and E. A. Wachter, Non-Destructive Inspection of Graphite-Epoxy Composites for Heat Damage Using Laser-Induced Fluorescence, Applied Spectroscopy, 1995.
5. User's Guide and Manual for S1000, PC 1000 and S2000 Series Spectrometer Systems, Ocean Optics, Inc, 1997.
6. Data acquisition system components, National Instruments Web Site.
7. LIF Portable System, Computer Instrument Interface, Inc, 1999.
8. Acousto-Optic Tunable Filter, Brimose, 1996
9. CCDOPS for Windows 95, Santa Barbara Instrument Group, 1999
10. Hewlett Packard, (1996). HP 8647A Signal Generator.
11. Farina, D.J. and Duffy, J. (1997). Thermal Mapping of Integrated Circuits Using LabView and IMAQ vision. Image Therm Engineering Inc.
12. National Instruments, (1996). LabView Tutorial Manual, Austin, TX.
13. Fisher, W. G., Meyer, K.E., and Wachter (1996). Laser Induced Fluorescence Imaging of Thermal Damage in Polymer Composites, Oak Ridge National Laboratory, Oak Ridge, TN.
14. R.M. Collins (1994), NDI for Heat Damaged Advanced Composites: Final Report on Characterization and NDE of Heat Damage in Graphite/Epoxy Composite.
15. Paul Kulowitch (1999), Presentation on: Detecting Heat Damage in Composites using Laser Induced Fluorescence.
16. IDL Basics, IDL version 5.0 (1997).

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Figure 1.  The Portable Laser Induced Fluorescence System

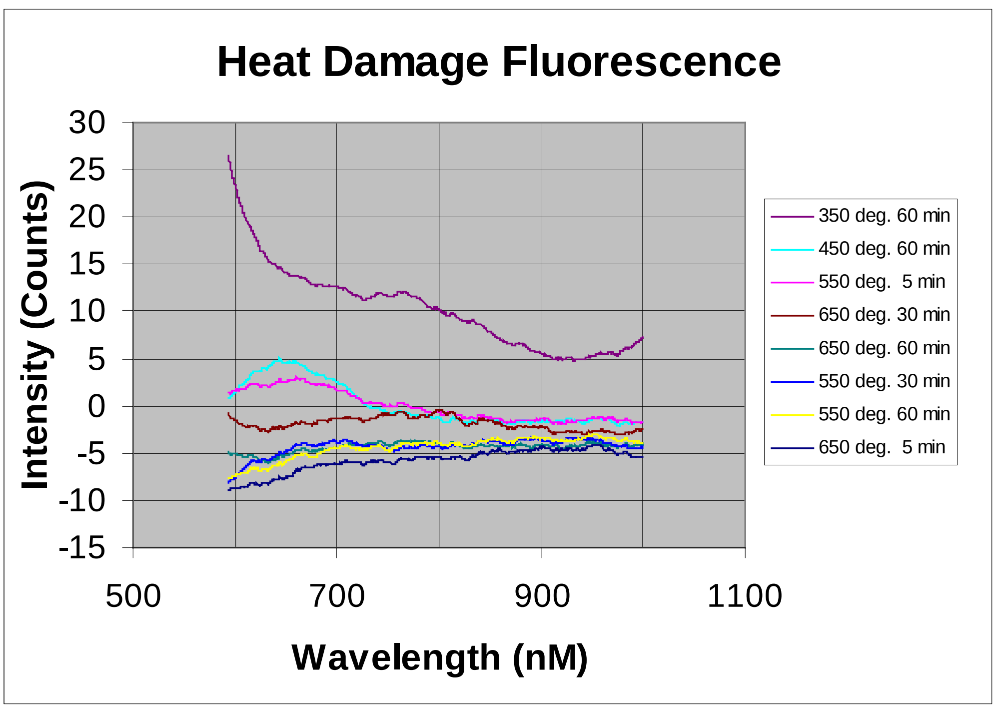


Figure 2.  The Fluorescence Spectrum of Various Heat Damaged Coupons (sample-reference)

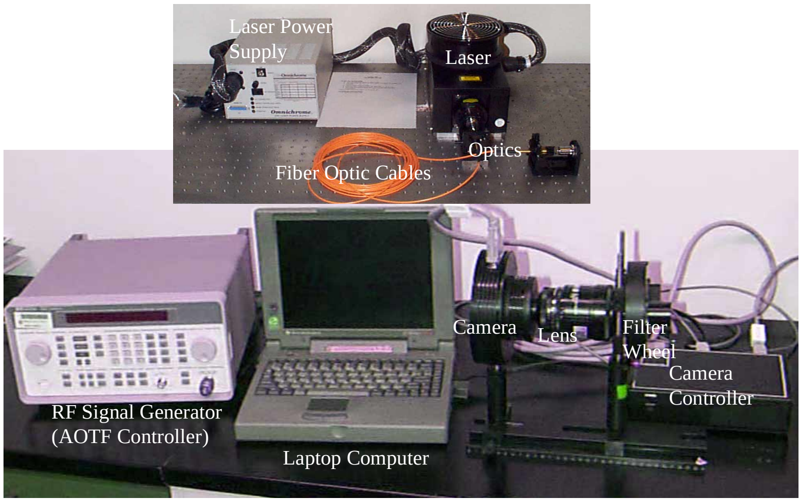

Figure 3. The Laser Induced Fluorescence Imaging System

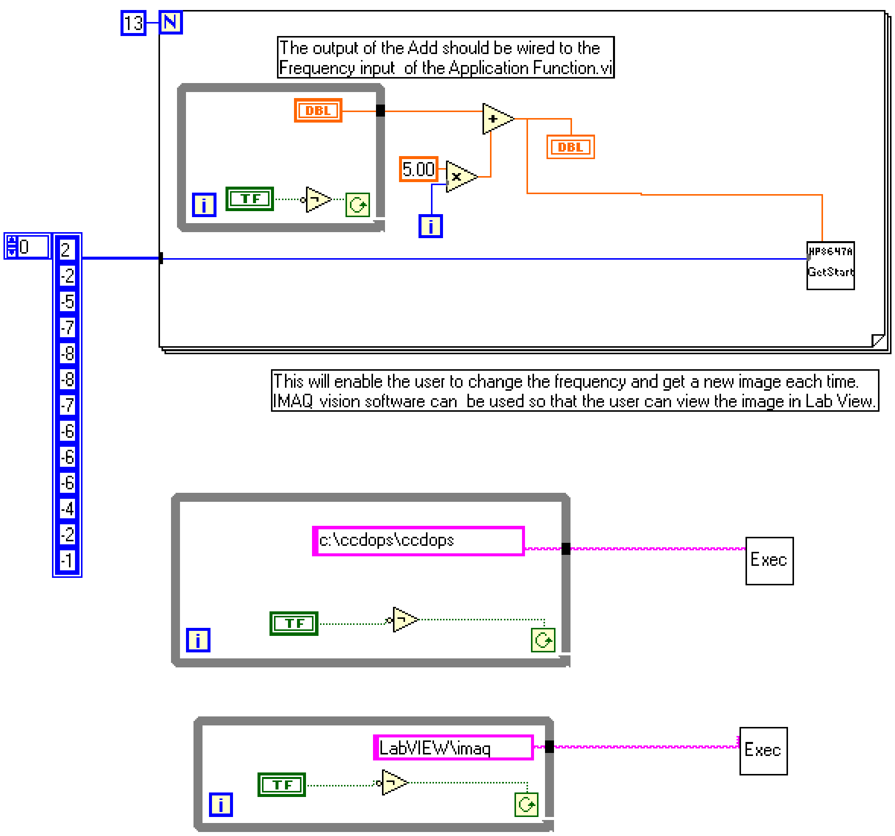

Figure 4. The VI Wiring Diagram for Controlling the AOTF.