Modelling of Thermal Storage in Damaged Composite Structures using Time Displaced Gradient Field Technique (TDGF)

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***Abstract*—This paper presents a new approach to composite surface characterization using Gradient Field time displacement. The new technique employs calculation of thermally charged regions within a composite structure as a result of each area gradient and then correlates the regions (storage areas) using a time displaced (Lag) model. The resulting data show that a rate-dependent model is fit to describe the behavior of damaged areas within a composite structure, which act as energy storage elements. The rate of dissipation of stored energy per region contributes to the shape and area of the resulting correlated Lag curve.**

***Keywords*—Gradient norm; edge detection; gray level mapping; segmentation; rate-dependent; lag; thermal images**

I. Introduction

Image enhancement is critical in image processing. Normally image enhancement is basically achieved using histogram equalization or one of its related techniques with no provision of proper mathematical model for the intensity variation associated with histogram equalization. Also, histogram equalization uses Probability Distribution Function (PDF) and Cumulative Distribution Function (CDF) and both assume uniform distribution, which is not applicable in many cases.

This problem can be resolved using gradient analysis or correlated gradient with histogram analysis. Such a unique concept has been employed for specific applications, such as, deblurring and image restoration [1]-[7].

Edge detection is an extremely important technique in image processing and image analysis. Edge detection process preserve important image structural features. Edge Detection involves taking steps in the process of locating the sharp edges which are discontinuous that result in variation in pixels intensities, thus, defining boundaries within the image [8]-[11].

Composite structures continue to be used widely in aerospace and automotive applications due to its light weight coupled with high strength. There is a growing interest in the application of thermal methods for nondestructive testing (NDT) of composite components. There are many gains using thermal NDT as compared to other methods, as its capable of covering large and complex areas without direct contact, and it produces results in a reasonably short time. Thermography has a good potential for detection of various abnormalities, such as delamination, and disbands.

Non-uniform composite structures and/or damaged composites will most of the time result in the creation of edges within the fiber-matrix system. Consequently, segmentation will occur and subdivides the composite image into regions. The number of regions formed as a result of segmentation depends on the type of damage a structure suffered. The segmented image is a function of both discontinuity and uniformity. Both factors can be used to establish similarity and level of damage as a result of abrupt change or edges [12]-[16].

Detecting damage using thermal images produced as a result of testing of composite structures is a challenging task owing to their variable appearance and the wide range of shapes and orientations that a damage can cause. The first need is a robust feature set that allows for damaged areas to be discriminated efficiently, even in cluttered backgrounds under difficult illumination. The second need is for a good mathematical model that covers effect of thermal energy on image properties due to the existence of non-uniform or damaged composite structure [17]-[21]. In addition, Knowledge of the thermal conductivity of the composite structure is essential in assessing and modelling heat transfer through fiber and matrix.

At present, active thermal imaging is regularly used for inspection during manufacturing and in service to inspect composite parts and units. The technique can be used to specify damaged areas and their boundaries. The technique measures the difference between the temperature of a defect area and a defect-free one. Processing of the results of can be achieved using dynamic thermal tomography technique fast Fourier transform.

In this work, a new approach to using gradient field analysis is applied to PVT images of composite structures, which results in a new approach in detecting and analysing composite structure damage, which is comparable in its approach to the active thermal imaging technique. The presented technique in the work is based on correlative displacement of gradient fields associated with damaged areas of composite structures identified as a result of energy based segmentation due to energy storage within the composite structure that results in thermal edges caused by structural damage.

II. Materials and Methods

The main objective is to use segmentation of thermal charged regions to detect damage. Damaged areas will vary in their energy storage in comparison to undamaged areas, resulting in thermal edges. Such a phenomenon can be realized through gradient application to captured images over periods of time. Pulse Video Thermography (PVT) is employed in the testing. The used equipment comprised a heating source and thermal imaging system. Pulses obtained by discharging energy pulses through flash tubes, which are directed at the tested structure. The tested structure consisted of 5mm thick Reaction Injection Molding (RIM) composites. The obtained thermal images converted to gray levels before applying segmentation algorithm as a function of Gradient Field (GF). Different levels of threshold used to obtain an optimum boundary isolation and region segmentation. Fig. 1 shows the experimental arrangement.

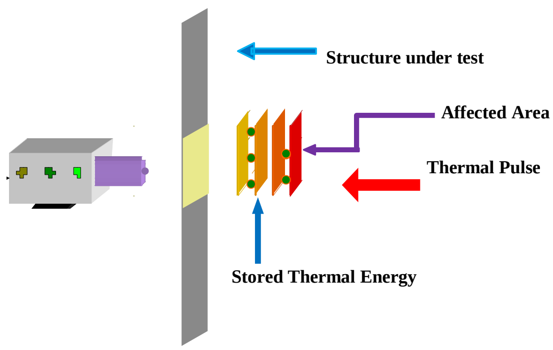

Fig. 1. Experimental setup.

III. Results

Fig. 2 to 4 show the tested component, at sampled intervals {13, 18, 23} minutes.

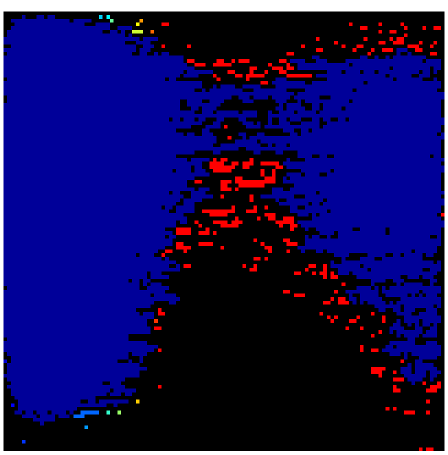

Fig. 2. Jet coloring of thermal image after 13 minutes.

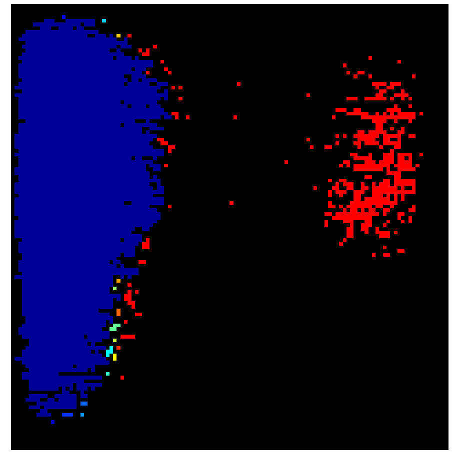

Fig. 3. Jet coloring of thermal image after 18 minutes.

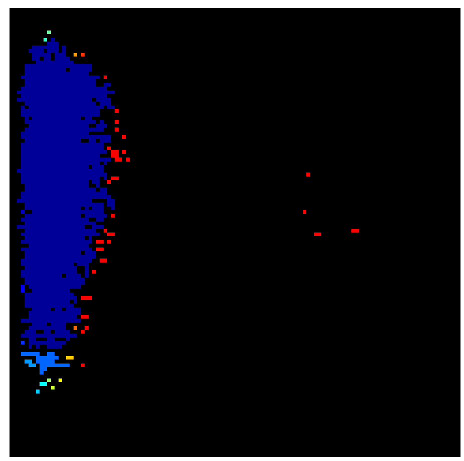

Fig. 4. Jet coloring of thermal image after 23 minutes.

Fig. 5 to 7 show the Gradient Field for each of the time sampled thermal images.

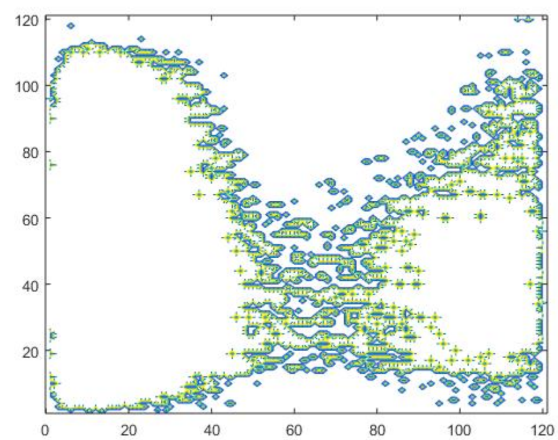

Fig. 5. Gradient field of thermal image after 13 minutes (coordinates represent pixels with image area of 120 by 120 by 3).

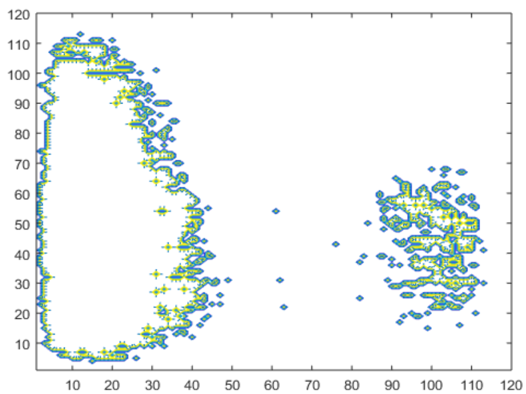

Fig. 6. Gradient field of thermal image after 18 minutes coordinates represent pixels with image area of 120 by 120 by 3).

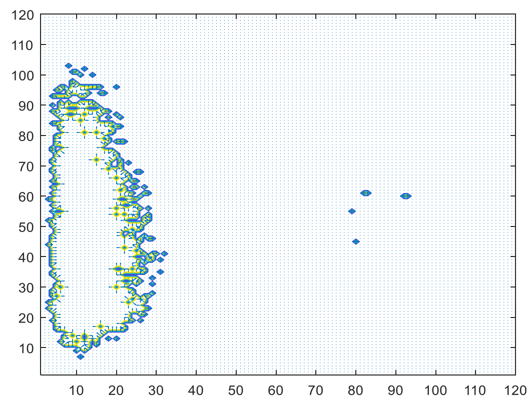

Fig. 7. Gradient field of thermal image after 23 minutes coordinates represent pixels with image area of 120 by 120 by 3).

IV. Analysis and Discussion

The observed Gradient field indicates four stages of thermal interaction between the composite sample under test and the thermally applied pulse:

A. *Initial absorption (t=t+)*: The whole structure is subjected to the applied pulse of energy with approximately equal distribution of intensity levels and pixel population over the structural area.

B. *Second stage (t=13 minutes)*: Two interconnected and thermally charged areas appear, with the rest of the areas discharged. The two touching areas (inter-thermal convergence) exchange thermal energy with each other and with the rest of the composite structure.

C. *Third stage (t=18 minutes)*: Two thermally charged areas, with well-defined boundaries (inter-thermal divergence and intra-thermal convergence) observed as a result of the areas in the second stage relinquished. This is due to thermal discharge of stored energy.

D. *Fourth stage (t = 23 minutes)*: Mainly one area is left, which is associated with the highest level of surface non-uniformity(damage), as other parts have come to a total thermal discharge and heat dissipation.

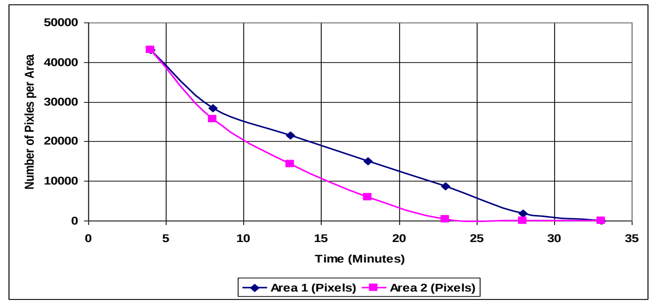

Fig. 8. Relationship between the two thermally charged regions in the tested composite.

Fig. 8 shows the relationship between the time responses of the two thermally charged arras within the tested composite structure. From the plots the relationship between the two charged areas representation can be modelled using a Rate-Dependent model as it is evident that during the thermal discharge process one thermal energy is exchanged between the two mainly charged regions (damaged areas) of tested composite structure, thus introducing a time delay or lag between the discharging activities of the two main regions. This introduce two main cycles considered in the proposed model:

1) Primary thermal charge-discharge cycle as a function of the applied PVT pulse.

2) Secondary thermal charge-discharge cycle as a function of damaged area size.

Both processes follow an outward direction. In general, the model is represented as in (1).

$$A_1(t) = R_{initial} - \int_0^{\infty} A_1(t-\tau)d\tau \tag{1}$$

$$A_2(t) = R_{initial} - \int_0^{\infty} A_2(t-\tau)d\tau \tag{2}$$

$$Lag(t) = |A_1(t) - A_2(t)| \tag{3}$$

$$Lag(t) = \left| \int_0^T A_1(t-\tau)d\tau - \int_0^T A_2(t-\tau)d\tau \right| \tag{4}$$

From the results, it is observed that one area will discharge at a faster rate and hence thermal decay will occur within the integration interval of the second area. Thus, (4) becomes (assume here that A_2 discharges at a faster rate):

$$Lag(t) = \left| \left[\int_0^{t_1} A_1(t-\tau)d\tau + \int_{t_1}^{T} A_1(t-\tau)d\tau \right] - \int_0^{t_1} A_2(t-\tau)d\tau \right| \tag{5}$$

where T is the maximum testing time. Thus:

$$Lag(t) = \left| \left[\int_0^{t_1} A_1(t-\tau)d\tau - \int_0^{t_1} A_2(t-\tau)d\tau \right] + \int_{t_1}^{T} A_1(t-\tau)d\tau \right| \tag{6}$$

which gives:

$$Lag(t) = \left| \left[\left(\int_0^{t_1} A_1(t-\tau) - A_2(t-\tau) \right) d\tau \right] + \int_{t_1}^{T} A_1(t-\tau) d\tau \right| \quad (7)$$

From (7), both A_2 and A_1 can be obtained as a function of each other:

$$A_1(t) = lag(t) - A_2(t) \quad (8)$$

$$A_2(t) = lag(t) - A_1(t) \quad (9)$$

Applying observations to (7) and noting that one region will undergo decay at a faster rate than the other (depending on which time limit is critical to show critical damage), results in the following:

$$Lag(t) = \left| \left[\left(\int_0^{t_1} A_1(t-\tau) - 0 \right) d\tau \right] + \int_{t_1}^{T} A_1(t-\tau) d\tau \right| \quad (10)$$

Which gives:

$$Lag(t) = \left| \left[\left(\int_0^{t_1} A_1(t-\tau) \right) d\tau \right] + \int_{t_1}^{T} A_1(t-\tau) d\tau \right| \quad (11)$$

Hence:

$$Lag(t) = \left| \int_0^{t_1} A_1(t-\tau) + \int_{t_1}^{T} A_1(t-\tau) d\tau \right| \quad (12)$$

Thus

$$Lag(t) = \left| \int_0^{T} A_1(t-\tau) d\tau \right| \quad (13)$$

Equation (13) indicates that a main area of damage is present in the tested composite structure.

The previous set of equations can be applied to any number of adjacently charged regions by extending (7) to include a set of time limits. Thus, allowing for various levels of charged regions to discharge their thermal energy and resulting in a tabulation of regions that contain fiber-matrix problems. This will allow for detailed analysis of causing effects and an enhanced process of manufacturing.

Fig. 9 show another dimension to the kind of relationship between the observed charged regions plotted over additional time intervals. From the figure, the following is observed:

1) An almost symmetrical difference curve as a function of time.

2) The maximum Area (pixel) difference occurs at t=18 minutes. Thus indicating a total separation between the two observed regions and the start of each region specified by an area of pixel population to diminish over a period of time.

3) The difference curve highlights what the Lag function describes and could alternatively be represented as in (14):

$$Diff = \left| \left(\frac{dA_2}{dt} \right) - \left(\frac{dA_1}{dt} \right) \right| \quad (14)$$

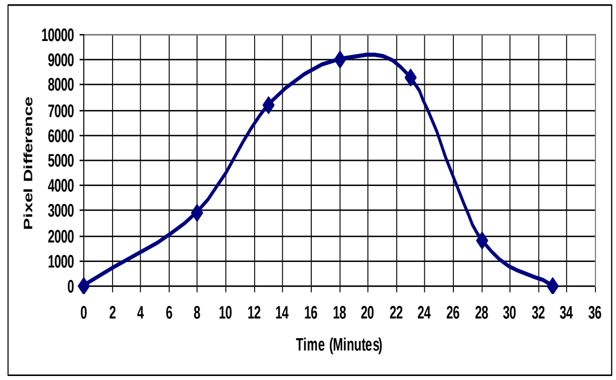

Fig. 9. Relationship (difference) between the two thermally charged regions in the tested composite.

Equation (14) also represents a time-relative change of segmented (damaged) areas that are separated by edges.

V. Conclusions

The proposed technique is an excellent beginning to Characterize damage in composite structures through edge detection and region segmentation using gradient field as a function of time displacement. From the obtained images and the mathematical model, the behavior of the charged regions in relations to each other can be quantified in Table I. The initial fully charged sample is (120 by 120 by 3 =43200). The factor of 3 is due to the conversion from color to gray level. The discharging relationship is presented in Fig. 10.

TABLE I. Relationship between Thermally Charged Regions

Time (min)	A_1	A_2	Ratio ($A_2 : A_1$
t=t+	43200	43200	Initial Charge
8	28500	25600	0.9
13	21600	14400	0.7
18	15000	6000	0.4
23	8700	400	0.1
28	1800	0	0

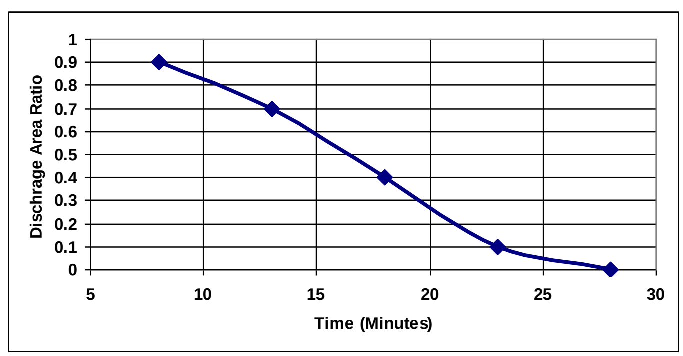

Fig. 10. Discharge relationship between two damaged areas in a composite structure.

It is evident the power law behavior of the discharging process of both damaged areas as a function of time and composite structure properties. The power law curve shows similar characteristics to Ostwald de Waele power law Model.

The presented technique is promising, and leads to potential development of detailed mathematical models covering the thermal behavior of composites by applying a more comprehensive version of the Gradient Field technique that takes into account the presented mathematical model, the optimum threshold level, type and structure of the tested composite component and various sources of thermal energy.

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