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Research Letter

Calibrated Pulse-Thermography Procedure for Inspecting HDPE

Mohammed A. Omar,[1] Yi Zhou,[2] Rohit Parvataneni,[2] and Eric Planting[2]

[1] *International Center for Automotive Research (CU-ICAR), Clemson University, 340 Campbell Jr. Graduate Engineering Center (CGEC), Greenville, SC 29607, USA*
[2] *Department of Mechanical Engineering, Clemson University, Clemson, SC 29634, USA*

Correspondence should be addressed to Mohammed A. Omar, momar@clemson.edu

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This manuscript discusses the application of a pulse-thermography modality to evaluate the integrity of a high-density polyethylene HDPE joint for delamination, in nonintrusive manner. The inspected HDPE structure is a twin-cup shape, molded through extrusion, and the inspection system comprises a high-intensity, short-duration radiation pulse to excite thermal emission; the text calibrates the experiment settings (pulse duration, and detector sampling rate) to accommodate HDPE bulks thermal response. The acquired thermal scans are processed through new contrast computation named "self-referencing", to investigate the joint tensile strength and further map its adhesion interface in real-time. The proposed system (hardware, software combination) performance is assessed through an ultrasound C-scan validation and further benchmarked using a standard pulse phase thermography (PPT) routine.

1. INTRODUCTION

Pulse or flash thermography is used in nonintrusively test and to evaluate bulks' subsurface based on the thermal contrast between its different interfaces (i.e., different conduction rates). Due to its reliance on thermal conduction, this modality has been applied for different classes of materials (isotropic, anisotropic ferrous, nonferrous, etc.) to detect variety of defectives; cracks and delaminations in CFRP/GFRP composites in [1], and for concrete structures in [2]. This manuscript demonstrates the application of pulse thermography to quantitatively evaluate the bond strength of HDPE molded joints, and map its adhesion interface. The quantitative evaluation is done through correlating the thermographic results with the pull force needed to break the joint using a tensile machine, which is the current standard testing method. Additionally, the synthesized adhesion interface is further validated with ultrasonic C-scan. A cross section of the inspected joint is displayed in Figure 1, which shows the joint dimension, shape, and inspected area. The main deviations encountered in such joints can be summarized into: structural and adhesive related. The structural aspect comprises any misalignment in the joint structure and diameter of contact at the neck region; while, the adhesion defects include adhesion layer thickness, uniformity, and delaminations. Both classes of variations affect the structure performance through its impact on joints' breakage modes, and its ultimate joint strength.

2. EXPERIMENTAL APPROACH

Due to the production constraints in terms of production rate and automation level in addition to the warranty costs and its safety implications, a noncontact, real-time inspection system is pursued, to evaluate 100% of the products. Even through ultrasound scanning is effective in evaluating both defective classes quantitatively, the need to an automated, full-geometry inspection scheme under one minute, motivated a two-dimensional vision-based approach. Thermal imaging or thermography has been used

successfully in several two-dimensional, real-time industrial implementations; as in quantifying the thickness of wet paint when applied over fuel containers in [3], and over complicated car shell geometries in [4]. In current application, a pulse thermographic procedure guarantees the two-dimensional coverage of inspected joint in real-time, with fully automated data correlation and processing. The developed system comprises a high-intensity, short 6400 joules of radiation perturbation (product of BALCAR, France), to excite thermal emission. While an uncooled microbolometric, vanadium oxide (VOx) coated 320 × 240 focal plane array (Product of FLIR, MA) is used to acquire the thermal response (emission counts), at up to 30 Hz sampling. The stimulation source and the thermal detector can be configured in either a reflection mode, where both are set in the same side, or in transmission mode, where they are set in opposite sides of the inspected joint, current configuration applies a reflection mode, to accommodate the short inspection time. To set the system parameters in terms of pulse, duration, intensity, and the camera acquisition rate, a thermal calibration for the HDPE is warranted. To do this we start with the facial thermal response of the inspected material, when considered as one-dimensional heat propagation in an opaque bulk, which can be mathematically described in (1) from [5]:

$$T_s(0,t) = 2\frac{I_0}{k}\sqrt{\frac{\alpha t}{\pi}}\left[1 + 2\sqrt{\pi\sum_{n=1}^{\infty}\left\{\frac{\varepsilon_1-\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right\}^n \text{ierfc}\left(\frac{nd}{\sqrt{\alpha t}}\right)}\right], \tag{1}$$

where, I_0 is the absorbed energy density of the pulse, α is the thermal diffusivity of the HDPE, k is its thermal conductivity, d is the HDPE layer thickness, and ε is the effuisivity (or thermal inertia $\varepsilon = \sqrt{k \times \rho \times C_p}$) for the HDPE (subscript 1), and the delaminated layer (subscript 2), which is simulated as an air interface. Then to decide on an optimized duration t_p for a rectangular pulse, the response from (1) is manipulated into (2).

$$T_p(0,t) = T_s(0,t) - T_s(0,t-t_p) \quad \text{for } t > t_p. \tag{2}$$

Equation (2) graphical representation in Figure 2(a) provides the time of maximum contrast between the defective and its surroundings by monitoring the corresponding time for maximum contrast. The plot in Figure 2(a) indicates that for the thermal reflection coefficient $\Gamma = \{(\varepsilon_1 - \varepsilon_2)/(\varepsilon_1 + \varepsilon_2)\}$ between an air interface and HDPE bulk of 0.94, the best observation time t_{obs} is found to be within $Fo = 0.65$, which means that the pulse duration should be $t_{\text{obs}} = Fo(d^2/\alpha) = 4.22$ seconds, for HDPE with $k = 0.5\,\text{W/m·K}$, $\rho = 950\,\text{kg/m}^3$, and $C_p = 1900\,\text{J/K·kg}$, while the delamination is embedded at 0.5 cm (i.e., at the adhesion interface). Thus, the camera acquisition rate and duration should accommodate such time window; such that the experiment duration prevents missing the maximum contrast signal while the acquisition rate allows for good sampling because some time-averaging might be needed; the pulse is set at 20 milliseconds duration with a detector acquisition rate of 20 Hz for one minute. To adjust the calibration procedure for defectives

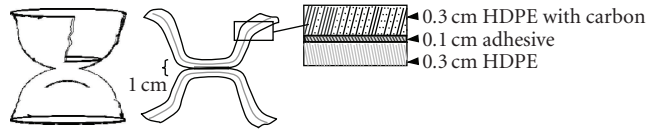

Figure 1: HDPE joint under inspection, showing joint structure, cross-section, and material layered structure.

located at different depths, we propose $(\partial T_p/\partial d)(0,t)$ to describe the depth contrast in (3), which is graphically displayed in Figure 2(b):

$$\frac{\partial T_p}{\partial d}(0,t) = \begin{cases} \dfrac{\partial T_s}{\partial d}, & t \le t_p \\ \dfrac{\partial T_s}{\partial d}(t) - \dfrac{\partial T_s}{\partial d}(t-t_p), & t > t_p \end{cases}$$

while,

$$\frac{\partial T_s}{\partial d}(0,t) = -4 \times \frac{I_0}{k}\sum_{n=1}^{\infty} n(\Gamma^n)\text{erfc}\left(\frac{n}{\sqrt{Fo}}\right). \tag{3}$$

3. DATA PROCESSING AND CORRELATION

Several calculation options exist for processing pulse-thermography sequences to translate the temperature-time history into subsurface maps, which retrieve any embedded delaminated locations and their shape. However, some of these routines as thermal signal reconstruction (TSR) [6] requires a priori knowledge of the defectives depth and their lateral dimensions, in other words their aspect ratio (depth/lateral dimension), to provide accurate depth predictions. Additionally, other routines such as pulse phase thermography PPT [7] provide inconsistent predictions when varying the sampling rate and/or the experiment duration [8, 9]. So, in this application we utilize a novel processing routine named "self-referencing" presented in [10], due to its insensitivity to implants aspect ratio and experiment variations. The self-referencing calculations extract the temperature-time history of each pixel location T_{pix} and compare its values to that of its neighbors' statistics mainly T_{avg} mean and standard deviation σ_{surr}. Then following the criteria in (4), a contrast matrix is initiated to describe the deviation from the defect-free behavior, additionally a time matrix is established to track the time of maximum contrast. Finally, to produce the depth map, the contrast $C_{\max}$ and time $t_{\max}$ matrices are used in (5) from [11], for each pixel location (i, j) to yield the defective depth D at that location:

$$|T_{\text{pix}} - T_{\text{avg}}| \ge \eta \cdot \sigma_{\text{surr}(i,j)}. \tag{4}$$

$$D = a\left[\sqrt{t_{\max}(i,j)}C_{\max}(i,j)^b\right]. \tag{5}$$

The resulted contrast and time matrices are displayed in Figure 3, in addition to the synthesized depth map using the proposed approach.

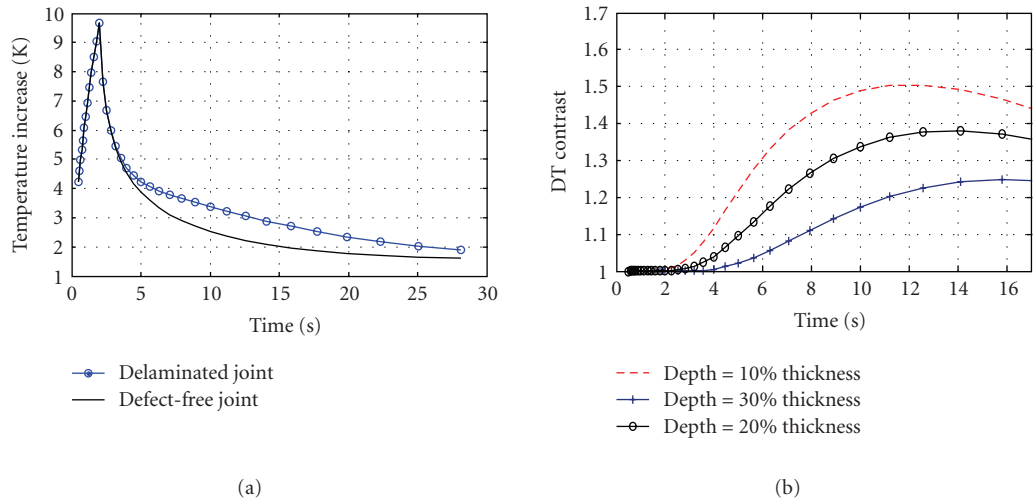

FIGURE 2: (a) Response to rectangular pulse, showing the departure time from defect free cooling, (b) thermal contrast variation with delamination depth.

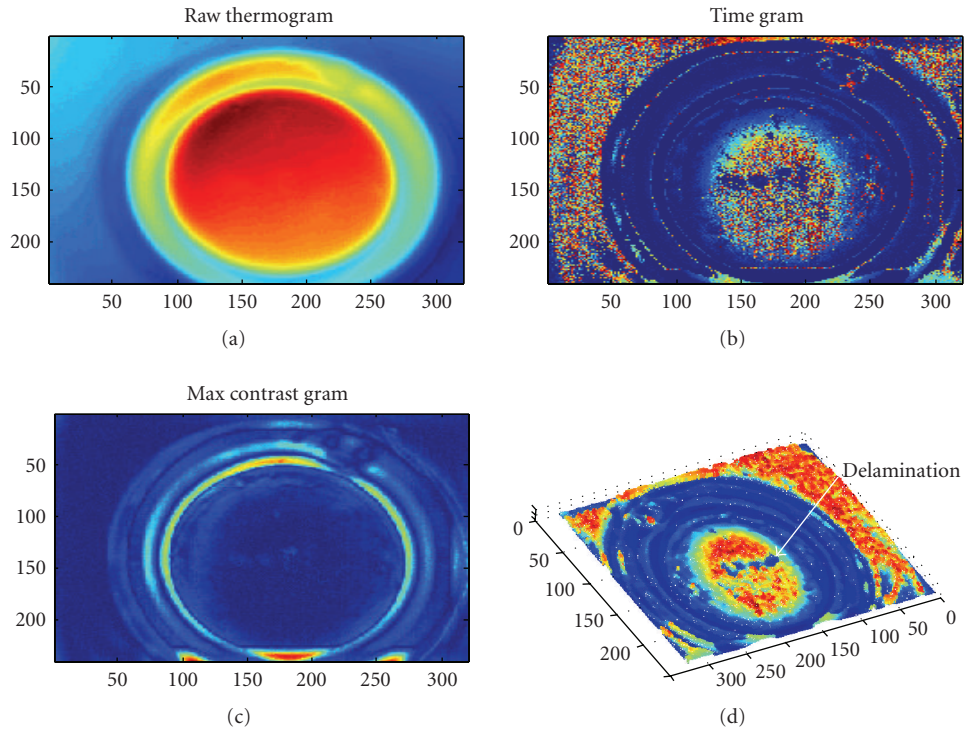

FIGURE 3: Sequence of self-referencing code showing the (a) raw-thermogram, (b) time-gram, (c) contrast-gram, (d) synthetic adhesion map.

To benchmark the proposed routine, an ultrasound C-scan is acquired utilizing an Ultrascan 5 transducer (Product of US Ultratek, CA), at a frequency of 5 MHz, and a sampling of 100 MHz and a spatial X-Y increment of ~3 mm. The C-scan is displayed in Figure 4(a), which shows a clear agreement between the pulse-thermography results and those of the C-scan, further computing the %error in the depth-thermogram results in 15%. Additionally, using a well publicized routine in thermography literature PPT, results in Figure 4(b). Finally, the joint tensile strength is investigated by correlating it with the thermal conduction heating profile across the joint, which is achieved through a transmission mode of thermography. Figure 5 from [12] plots the conduction propagation rates for different pulled samples while the legend indicates the tensile force used to break the corresponding joint.

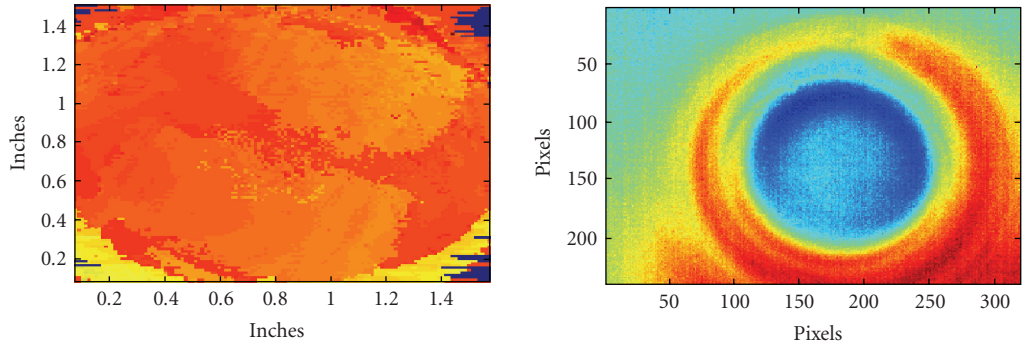

FIGURE 4: (a) C-scan result, (b) PPT phase image.

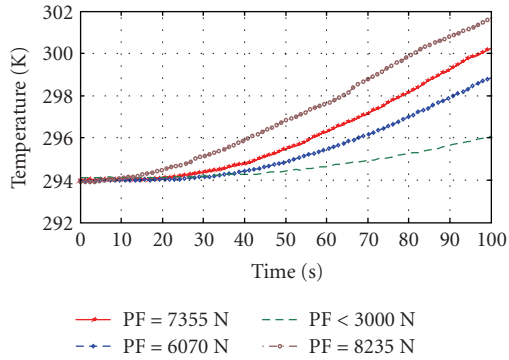

FIGURE 5: Temperature evolution curves for transmission mode thermography, legends corresponding tensile force.

4. CONCLUSION

The manuscript presented a flash-thermography, nonintrusive procedure to inspect HDPE molded joints. The text presented a new method to calibrate the thermographic procedure to accommodate the inspected bulk in two domains, the hardware by calibrating the pulse duration, detector sampling rate, and using the material thermal response for a square pulse with finite duration. Additionally, the software domain presented a robust, self-calibrated calculation to produce the adhesion layer thickness. C-scan results validated the performance of the proposed scheme, while the temperature evolution curves was in agreement with tensile force predictions.

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