Transient thermography is used in the detection and visualization of sub-surface flaws. It is proposed as an alternative to popular non-destructive (NDT) infrared thermography methods such as pulsed and lock-in thermography. The transient method is preferred for its simple application, relatively fast inspection times and high thermal contrast for low thermal defect resistance cases. It further enables the use of an entry-level infrared camera. Particular interest was placed to investigate small diameter and low resistance defects, such as thin Teflon® inclusions and air gaps that simulate open and closed delaminations expected in composite materials. Appropriate image processing methods from literature are also reviewed for transient thermography to enhance the subtle defect signatures. The study further inspects samples from industry proposing transient thermography as a simple quantitative NDT method for defect sizing. The smallest detectable anomaly was found to be 1 mm wide in various industrial samples, which was a spatial resolution limitation of the infrared camera. The findings of the artificial samples reported a maximum defect depth up to 5 mm for glass and carbon fibre reinforced epoxy. The method was particularly better for low thermal diffusivity materials as deeper defects where detected in the glass fibre composites than in the carbon composites.

**Additional keywords:** Infrared camera; non-destructive testing; thermography.

1 **Introduction**

Non-destructive testing with infrared thermography (IRT) has gained more attention over the last 40 years. IRT presents favourable performance specifically towards composite material testing considering that most FRP composites are relatively thin structures and IRT is inherently sensitive to near-surface anomalies [1]. Equally there is a shift towards automated NDT testing [2] for batch product processing and IRT has a potential to further simplify user interaction and interpretation through images known as thermograms.

Optical thermography describes a method in which a material’s surface is heated by a photo-thermal energy source and the surface temperature distribution is measured using an infrared camera. Internal anomalies are observed as hot or cold spots as a result of a temperature contrast between a sound (free of defects) and defective region.

- a. Department of Mechanical and Mechatronic Engineering, Stellenbosch University, South Africa. jayjay.jk@gmail.com
- b. Department of Mechanical and Mechatronic Engineering, Stellenbosch University, South Africa. gventer@sun.ac.za
- c. Department of Mechanical and Mechatronic Engineering, Stellenbosch University, South Africa. kschreve@sun.ac.za

The most widely used directions in optical thermography have been towards pulsed and lock-in thermography. Lock-in thermography requires periodic heat input to stimulate an oscillating steady-state thermal response on a target material’s surface. In addition to the long inspection times required to obtain thermal stabilization, the method requires the inspection to be performed for other modulating frequencies in order to detect all flaw depths. This is because the modulating frequency of the input is linked to the probing depth of the inspection. In pulsed thermography the surface is flashed with high-power xenon lamps. These lamp systems are typically more expensive than halogen flood lamps and both methods require additional power controllers and high-current power supplies.

This study focuses on the application of transient thermography which requires heating of the target surface by a constant heat flux for a duration that lasts from one second to several minutes using halogen lamps. A typical transient setup is seen in figure 1. Transient thermography could use one of two heating methods: step and square-pulse heating. Both these methods rely on observing the temperature rise of a surface, while square pulse thermography also observes the subsequent thermal decay after the heat flux has been removed.

Transient methods are expected to combine the advantages of both lock-in and pulsed thermography without sharing the drawback of long inspection times of lock-in and the need for costly light systems. The particular benefit in transient thermography is that the total heat-input can be easily increased by increasing the power and duration of the heat source. This makes transient thermography a promising method for inspecting deeper defects than pulse thermography [3]. There have been few attempts made with inspection of defects with transient thermography and the few applications have been made without any theoretical basis[4].

This study also evaluates the difference between step and square pulse heating while assessing the viability of several image processing techniques related to IRT.

**Figure 1:** Transient thermography setup.
Non-destructive Testing with Transient Thermography on Composite Materials

2 Experimental Setup

2.1 Target Samples

Composites are prone to flaws such as delaminations, voids and inclusions that do not accurately represent flat-bottom holes, which are commonly evaluated in experimental work. Therefore, the inspection of thin artificial air-gaps and Teflon® delaminations were investigated. The configurations of the defects within the composite laminates are given in figure 2.

The details of the samples are provided in table 1, where the first letter designates either carbon (C) or glass (G) fibre plain weave in epoxy resin, the number designates the fibre density in g/m² and T and A describe Teflon® inserts or air gap delaminations respectively. The defect depth was estimated from the total cured thickness and defect layer position.

The composite plates were created using vacuum bag moulding and ambiently cured using Ampreg 21 standard resin. The air-gaps were created by removing a Teflon® sleeve after the composite was cured.

Table 1: Depth of artificial flaws in figure 2.

<table>
<thead>
<tr>
<th>Insert</th>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness (mm)</td>
<td>(mm)</td>
<td>(mm)</td>
<td>(mm)</td>
</tr>
<tr>
<td>Teflon® Inserts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C200T</td>
<td>0.50</td>
<td>1.38</td>
<td>2.76</td>
</tr>
<tr>
<td>C200T*</td>
<td>0.25</td>
<td>1.42</td>
<td>2.84</td>
</tr>
<tr>
<td>G200T</td>
<td>0.50</td>
<td>1.35</td>
<td>2.70</td>
</tr>
<tr>
<td>G106T</td>
<td>0.50</td>
<td>1.31</td>
<td>2.62</td>
</tr>
<tr>
<td>Air Gap</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C200A</td>
<td>0.50</td>
<td>1.65</td>
<td>3.29</td>
</tr>
<tr>
<td>G200A</td>
<td>0.50</td>
<td>1.28</td>
<td>2.55</td>
</tr>
</tbody>
</table>

The thermal resistance, \( R \), of the defects can be calculated as \( R = \Delta z / k \), where \( \Delta z \) is the thickness and \( k \) is the thermal conductivity of the insert. The thermal resistance of the air-gap is approximately 0.021 KW⁻¹, which is about 10 times the thermal resistance of the Teflon® insert for the same thickness (0.002 KW⁻¹). The air-gap delaminations are expected to produce a higher thermal contrast for having a higher thermal resistance. With respect to the thermal resistance of flat-bottom holes, the thermal resistance tends towards infinity, which describes the highest possible contrast between defective and sound regions.

2.2 Stimulation and Acquisition

A symmetrical heat-source consisting of four 1000 W halogen-tungsten lamps was used, as seen in figure 3, that could produce two power outputs: 2000 and 4000 W. The lights were angled at 120° apart normal to the target surface to focus infrared reflections away from the camera and covered with a 5 mm tempered, fused-silica glass pane to remove residual reflections from the hot light filaments.

Data acquisition was performed with a FLIR® E60. The camera's detector is a focal plane array, uncooled microbolometer with a spatial resolution of 320 × 240 pixels. The camera is a medium-wave infrared camera (MWIR) operating in the 7.5 to 13 µm spectral band. The sampling frequency is limited to a maximum of 30 Hz with a noise equivalent temperature difference, NETD = 0.05 °C with an accuracy of 2 %.

Figure 2: Configurations of PTFE (Teflon®) and air-gap inclusions.

Figure 3: Four 1000 W halogen light setup.

2.3 Industrial Samples

Poorly-made samples from industry were additionally inspected to highlight the needs in industrial quality control inspection. These samples were either intentionally altered or had failed during the curing stage. The flaws were only made known once the inspection had been performed. Due to space being limited the reader is encouraged to find a more detailed inspection of the industrial samples in [5].

3 Processing Methods

Infrared images, known as thermograms, are mainly degraded with optical (vignetting, dead pixels, noise), emissivity and non-uniform heating effects. The local emissivity variation of the surface and the global emissivity of the different samples are both important to consider. At the same time, the thermograms contain subtle signatures of the subsurface variability in the material which often needs processing techniques to enhance the variability. Useful enhancement techniques for transient thermography include contrast methods, histogram equalization, principal component thermography (PCT), signal transforms (Fourier and wavelet transform), multiscale retinex and statistical methods (standardized statistical moments and matched filters). Traditional image processing methods are not discussed in detail here.

3.1 Contrast Methods

Contrast methods are the simplest form of enhancing detail in the thermograms, even though they require the selection of a sound area, \( S_a \). This area can be one pixel or the average of selected sound areas. The differential absolute contrast (DAC) and modified differential absolute contrast methods
elimates the need for the manual selection of Sa but rather require the selection of an image frame before defects begin to appear. However, the performance of the DAC methods did not perform well for transient thermography [5].

The four main contrast methods are [1]:

Absolute contrast:

$$C_{abs}(t) = T(t) - T_{Sa}(t)$$  \(1\)

Standard contrast:

$$C_{std}(t) = \frac{T(t) - T_{Sa}(t)}{T_{Sa}(t)}$$  \(2\)

Normalized contrast:

$$C_{norm}(t) = \frac{T(t)}{T_{Sa}(t)_{\max}} - \frac{T_{Sa}(t)}{T_{Sa}(t)_{\max}}$$  \(3\)

Running contrast:

$$C_{run}(t) = \frac{T(t) - T_{Sa}(t)}{T_{Sa}(t)}$$  \(4\)

The absolute contrast method is the classical contrast method while the standard contrast was developed to suppress impact of infrared reflections. Both the running and normalized contrast methods, which were further developed to reduce effects of emissivity and surface non-uniformity.

3.2 Principal Component Thermography

Principal component thermography (PCT) is based on an eigenvector transform which applies an orthogonal transformation to the thermal inspection data. PCT relies on singular value decomposition (SVD), which decomposes the data into a smaller set of orthogonal statistical modes, known as empirical orthogonal functions (EOFs). The EOFs represent a complete description of the spatial and temporal variability in the thermal sequence.

Assuming that the thermal data is a \(M \times N\) data matrix \(A\) (\(M > N\)), then the SVD can be applied to a matrix \(A\) that produces [6,7]:

$$A = U R V^T$$  \(5\)

where \(U\) is a \(M \times N\) matrix that contains the EOFs in each column, \(R\) is a diagonal \(N \times N\) matrix containing the absolute values of the eigenvalues (singular values) of \(A\) and \(V^T\) is an \(N \times N\) unitary matrix. In order to apply this to the thermal data-cube matrix, the total number of pixels \((N_x \times N_y)\) are rearranged into a single vector to condense the information as a single matrix \(A\) having dimensions \((N_x \times N_y) \times N_t\) with \(N_t\) designating the number of frames. Matrix \(A\) is then standardized to ensure uniform variance on a pixel-wise basis:

$$\tilde{A} = \frac{A - \mu_m}{\sigma_m}$$  \(6\)

where \(\mu_m\) and \(\sigma_m\) are the mean and standard deviation of the temperature-time response of a pixel.

The columns of \(U\), which describe the EOFs, can be rearranged from their vector form back into a set of frames.

3.3 Fourier Transform

The Fourier transform reconstructs the pixel’s temperature-time signal in the frequency space where amplitude and phase images can be retrieved. Phase images have shown to be less affected by surface emissivity, surface features and non-uniform contrasts. The discrete Fourier transform can be applied to the temperature history of each pixel using the Fast Fourier Transform (FFT) [8]

$$F_k = \sum_{n=0}^{N-1} T(n) \exp(-j2\pi nk/N) = Re_k + jIm_k$$  \(7\)

where \(j^2 = -1\), \(n = (0, 1, 2, \cdots, N - 1)\) defines the next sampling time for \(N\) sample points separated by a sampling interval \(t\) and \(k\) designates the frequency increment \((k = 0, 1, 2, \cdots, N)\).

The resulting one-dimensional Fourier coefficients produce real and complex terms, which can be separated and reshaped to produce discrete amplitude \(A\) and phase \(\phi\) images for each frequency component \(k\):

$$A_k = \sqrt{Re_k^2 + Im_k^2}$$  \(8\)

$$\phi_k = \tan^{-1}\left(\frac{Im_k}{Re_k}\right)$$  \(9\)

3.4 Wavelet Transform

The wavelet transform is an extension of the Fourier transform with the added benefit of preserving time information, since defect depth is a function of the square root of time [9]. The signal is decomposed through window functions containing a periodic waveform of limited duration, known as a wavelet. The basic wavelet transform can be seen as the convolution of the signal \(f(t)\) and daughter wavelet \(\psi_{ST}\), defined for a translation factor \(T\) and a scale factor \(S\):

$$W_f(S,T) = \int_{-\infty}^{\infty} f(t) \psi_{ST}(t) dt = \text{Re}_S + j\text{Im}_S$$  \(10\)

where \(*\) is the complex conjugate. The daughter wavelet \(\psi_{ST}\) is expressed as a scaled and translated replica of a single base wavelet called the mother wavelet \(\psi_m\):

$$\psi_{ST}(t) = \frac{1}{\sqrt{|S|}} \psi_m\left(\frac{t-T}{S}\right)$$  \(11\)

where the scaling factor \(S\) controls the width of the wavelet and the translation factor \(T\) controls the position of the wavelet along the analysed signal. The wavelet transform permits the use of many different mother wavelets \(\psi_m\).

The choice of the wavelet for thermographic analysis is desired to share the characteristic qualities of the Fourier transform and, hence, the complex Morlet wavelet is chosen as the mother wavelet [10]. The Morlet mother wavelet is defined as

$$\psi_m = \exp(-j\omega_0t)\exp\left(-\frac{t^2}{\tau^2}\right)$$  \(12\)

The phase and amplitude images can once again be obtained using equations 8 and 9. This time amplitude and phase images become available at different scales for the entire frame length and therefore creating a two-dimensional output for a one-dimensional input. To reduce the dimensionality, an appropriate scale can be chosen [5].

3.5 Multiscale Retinex

The multiscale retinex (MSR) algorithm is a photometric normalization technique [11]. This method enhances the local image contrast where the variations in grayscale intensities are better perceived by human eyes (retina). The mathematical form of the single scale retinex (SSR) is given as:

$$I_{SSR}(x,y) = \log[I_i(x,y)] - \log[I_i(x,y) * F(x,y)]$$  \(13\)

where \(I_i(x,y)\) is the input image and \(F(x,y)\) is the normalized kernel function.
Non-destructive Testing with Transient Thermography on Composite Materials

The classical assumption states that an image can be separated into \( I(x, y) = L(x, y) R(x, y) \), where \( L \) is the illumination and \( R \) is the scene reflectance components.

Now equation 13 can be rewritten as

\[
I_{SSR}(x, y) \approx \log \left( \frac{L(x, y) R(x, y)}{L \cdot R} \right)
\]

where the bars denote the weighted average. Since the illumination is assumed to vary gradually and smoothly, the illumination can be considered constant: \( L \approx l \). This leads to the simplification of equation 14 as

\[
I_{SSR}(x, y) \approx \log \left( \frac{R(x, y)}{R} \right)
\]

which is illumination independent.

The kernel function \( F(x, y) \) can be created with a Gaussian function:

\[
F(x, y) = C \exp \left( -\frac{x^2+y^2}{\sigma^2} \right)
\]

where \( \sigma \) is the filter’s standard deviation defined by the user. The constant \( C \) is the normalization factor such that

\[
\int F(x, y) \, dx \, dy = 1
\]

The multiscale retina builds on the SSR by repeating it for various scales and is the weighted sum of outputs:

\[
l_{MSR}(x, y) = \sum_{n=1}^{N} w_n \cdot I_{SSR}
\]

where \( w_n \) is the weight of each scale. Three scales where deemed good enough with the scales fixed as \( \sigma = 15, 80, 250 \) [5, 11].

### 3.6 Statistical Methods

The first statistical methods include standardized moments: skewness and kurtosis. Skewness, the third statistical standardized moment, measures the asymmetry of the probability distribution in the temperature-time history on a pixel-wise basis and is defined as [2]

\[
\text{skewness} = \frac{\sum_{i=1}^{N}(x_i-\mu)^3}{\sigma^3(N-1)}
\]

Kurtosis is the fourth standardized moment that measures flatness of the central mean of the probability distribution in the temperature-time history on a pixel-wise basis. Kurtosis is defined as [12]

\[
\text{kurtosis} = \frac{\sum_{i=1}^{N}(x_i-\mu)^4}{\sigma^4(N-1)}
\]

Other statistical methods include matched filters which are all based on the following assumption [13]:

\[
T_{\text{meas}} = \epsilon \cdot T_{\text{refl}} + T_{\text{ideal}}
\]

where \( T_{\text{meas}} \) is the measured temperature signal, \( T_{\text{refl}} \) is the temperature signal that describes defect information and \( T_{\text{ideal}} \) describes an ideal temperature signal unaffected by internal defects. Equation 21 can be rewritten in vector form respectively as \( \mathbf{x} = \mathbf{e} \cdot \mathbf{s} + \mathbf{w} \).

The matched filters aim to maximize \( T_{\text{refl}} \) (defect detail) while minimizing \( T_{\text{ideal}} \) based on the following objective model and constraint: max\( q^T \mathbf{s} \) subject to min\( q^T \mathbf{w} \).

The reflectance temperature, \( T_{\text{refl}} \), is not known from the measured signal and can be determined by selecting a sound zone:

\[
T_{\text{refl}} = T_{\text{meas}} - T_{\text{ideal}}
\]

The next four matched filter algorithms use \( T_{\text{refl}} (\mathbf{s}) \) as vector \( \mathbf{q} \). The spectral angle map (SAM) filter is defined as

\[
\text{SAM}(x_{ij}) = \frac{s^T \mathbf{x}_{ij}}{\sqrt{s^T \mathbf{C}^{-1} s \cdot \mathbf{x}_{ij}^T \mathbf{x}_{ij}}}
\]

The adaptive coherence estimator (ACE) adds the covariance matrix of the ideal temperature response, which incorporates the structural information of the target sample. The covariance matrix is expressed as \( \mathbf{C} = \frac{1}{MN} \sum_{k=1}^{MN} \mathbf{w}_k^T \mathbf{w}_k \) where \( MN \) is the number of pixels and the ACE filter is expressed as

\[
\text{ACE}(x_{ij}) = \frac{s^T \mathbf{C}^{-1} x_{ij}}{\sqrt{s^T \mathbf{C}^{-1} s \cdot x_{ij}^T \mathbf{C}^{-1} x_{ij}}}
\]

The t-statistic and F statistic filters are defined as

\[
\text{tstat}(x_{ij}) = \frac{s^T \mathbf{C}^{-1} x_{ij}}{\sqrt{x_{ij}^T \mathbf{C}^{-1} x_{ij} - \frac{q^2}{s^T \mathbf{C}^{-1} s}}}
\]

where \( q = \sqrt{\frac{1}{s^T \mathbf{C}^{-1} s}} \) and

\[
\text{Fstat}(x_{ij}) = (\text{tstat}(x_{ij}))^2
\]

### 4 Results and Discussion

The effects of heating, the chosen transient regime and processing technique are reviewed on the artificial samples. In addition, the application of transient thermography is explored on the industrial samples.

An increase in heating power, spectral power and duration for both transient regimes produced a proportional increase in defect contrast. The effect of power input and duration for two different defect depths are shown in figure 4.

The heating procedure lasted a total duration of 50 seconds, which was found to be long enough to produce a suitable defect contrast and prevent high temperatures that matched the glass-transition point of the epoxy resin. The 50 seconds duration also provides a short inspection scenario that is fairly competitive to pulsed thermography and surpasses the long heating times of lock-in.

![Figure 4: Effects of heating duration and power on defect contrast.](http://www.saimeche.org.za)
by the material’s thermal diffusivity. This describes the depth limitations of transient thermography.

Interestingly, for long heating times ($t > 30 \text{ s}$) the samples revealed a reduction in defect contrast as illustrated by figure 5. This may be a result of thermal equilibrium being reached through the layers of the material and greater lateral diffusion effects near the surface of the material.

For square pulse heating, a total time of 16 seconds ensured enough time remained to capture the decaying temperature signal but long enough to introduce a defect contrast for the deepest defect.

4.1 Step versus Square Pulse

In order to determine the differences between step and square pulse heating the best raw thermal contrast images of both the artificial samples are shown side-by-side in figures 6 to 11. Equally the differences between the samples can be noted.

Step heating displayed a sharper defect definition that better resembled actual defect shape. Square pulse heating was able to detect the same number of defects with better or similar image contrast for a lower total energy input. The square pulse heating also exhibited better defect detectability for low emissivity materials, such as the glass fibre composites.

Notably, the high thermal resistance of the air-gap defects displays a better contrast and definition in the raw thermograms. This concludes that there are different thermal contrast responses for the samples with the same composition sharing similar defect depths but different thermal resistances. Ultimately these contrast differences infer that determining defect depth using thermal contrast images cannot be performed, unless at least three defect depths are known \textit{a priori} to form an empirical relationship of depth.
4.2 Evaluating Processing Methods

The raw thermograms are individually processed with the reviewed processing algorithms. The sample, G106T is used as baseline sample to help compare the performance of each processing method for both square pulse and step heating. The raw images can be seen in figure 7.

Firstly, the contrast methods are seen to slightly improve the defect contrast of the sample for both transient methods in figures 12 to 15. However, the modified contrast methods like running and normalized do not remove the effects of surface emissivity as intended. Overall contrast was better in square pulse heating when using the contrast methods.

Figure 12: Absolute contrast: square pulse (left) and step (right) heating.

Figure 13: Standard contrast: square pulse (left) and step (right) heating.

Figure 14: Running contrast: square pulse (left) and step (right) heating.

Figure 15: Normalized contrast: square pulse (left) and step (right) heating.

The other reviewed processing methods are shown in figures 16 to 25 for the selected best contrast images. Other variability such as air-voids produced by the wet-layup procedure is also enhanced by many of the processing methods. The principal component thermography images display a reasonable description of the Teflon® defects while the Fourier transform produces a mediocre overall defect enhancement. The wavelet transform is seen to provide a more detail description of the Teflon® defects with a fairly uniform background that was originally contaminated with non-uniform heating effects. The multiscale retinex displays a similar result to the wavelet transform, however it is still contaminated with non-uniform heating effects.

Figure 16: 2nd Empirical orthogonal function (EOF) of PCT: square pulse (left) and step (right) heating.

Figure 17: Fourier transform at $f = 0.04$ Hz: square pulse (left) and step (right) heating.
The skewness and kurtosis images where seen to enhance the shallowest defects fairly well, while the deeper defects’ shapes are less identifiable. This may be a result of non-uniform heating of the original thermograms.

The matched filters, such as the spectral angle map (SAM) and adaptive coherence estimator (ACE) filters show some increased performance over the skewness and kurtosis processing methods. On the other hand, the t- and F statistic filters enhanced the shallowest defect fairly well but were inadequate in enhancing the deeper defects that had weaker contrasts. The statistical methods were beneficial as they produced a single image containing variability of the entire thermal sequence. These methods can be used in combination with other processing methods to simplify the inspection to a single enhanced image.
The deepest defects detected in the target samples after data processing methods are given in Table 2. All defects in the glass fibre composites were detectable while the shallowest Teflon® defects in the carbon fibre composites were only definable. The reason may be linked to the high conductivity of the carbon fibre leading to faster thermal equilibrium times. When thermal equilibrium is met, surface contrast no longer displays internal defects. Even for the carbon Teflon® sample with half the original delamination thickness (C200T*), the shallowest layer was still detectable.

Table 2: Deepest defect detectable in target samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C200A</td>
<td>4.9†</td>
</tr>
<tr>
<td>G200T</td>
<td>4†</td>
</tr>
<tr>
<td>G106T</td>
<td>3.9†</td>
</tr>
<tr>
<td>G200A</td>
<td>3.8†</td>
</tr>
<tr>
<td>C200T</td>
<td>2.7</td>
</tr>
<tr>
<td>C200T*</td>
<td>1.4</td>
</tr>
</tbody>
</table>

† indicates the deepest defect in the sample was detected.

To summarise, the processing methods aided in the identification of the defects and variability in the material as well as their shapes. The contrast methods displayed moderate improvement to the raw thermograms but are still affected by uneven contrast caused by non-uniform heating. The processing methods that showed best overall performance for transient thermography included multiscale retinex, principal component thermography and the wavelet transform. Multiscale retinex showed to be an effective method for both pre- and post-processing. The matched filters and contrast methods all required some user input for the optimal selection of defective or sound zones. The statistical methods were valuable in reducing the redundancy and the storage requirements of the thermal data. Other popular processing techniques used in pulsed thermography, which are not discussed here, did not perform well for transient thermography, such as the derivative images, polynomial coefficients, Markov error contrast and the differential absolute contrast methods (DAC). However, the thermographic signal reconstruction (TSR) was beneficial in noise cancellation and data reduction [5].

4.3 Industrial Samples

Two industrial samples are inspected and the best processing methods identified above are applied. Figure 26 displays a 10-ply glass-phenolic laminate with possible trapped material inclusions. The raw thermogram is processed with the wavelet transform and post-processed with multiscale retinex. Different void materials can be identified by different grayscale intensities and ply features become more noticeable.

Figure 27 displays a rejected glass-epoxy sandwich laminate with a honeycomb core, which was improperly vacuumed-sealed during curing. The raw thermograms were processed using principal component thermography and the 3rd empirical orthogonal function was selected. Again the thermograms were post-processed with the multiscale retinex method. Figure 27(c) shows variability (up to 1 mm wide) in resin build-up and non-uniformity in skin thickness through variations in grey level intensities. This should typical be a uniform greyscale intensity. Sub-surface ply details and the honeycomb core can be also detected.

4.4 Limitations

The general consensus in thermography is that depth information can be determined. However, depth estimation is limited to inversion methods based on contrast images, regardless of the processing method used on these contrast images [5]. The fundamental problem in thermographic...
inspection is that structural information is derived from the diffusion of heat that is influenced by finite defect size, thickness and thermal properties. There is also no intrinsic feature of heat flow that can be used to define a reference depth.

5 Conclusion
The main aim of this work reviewed two transient thermography methods, step and square-pulse heating, for their application into industry as a simple NDT method for the inspection of composites. Overall, this project proposes the application of transient thermography as a complementary or standalone NDT method that is relatively affordable and effective in the inspection of thin composites up to 5 mm.

Transient thermography as a NDT method simplifies the inspection of different sized specimens and speeds up the interpretation process when investigating the variability in composites. It allows the visualization of surface and internal variability for an arrangement of composite materials.

Unfortunately, depth information cannot be accurately determined without developing an empirical relationship between depth and contrast. An empirical relationship requires at least three known defect depths having the same thermal resistance which is influenced by the depth, thickness and inclusion material. Knowing the depth of defects can be considered less critical than the lateral size of a defect when thermography is limited to inspection of relatively thin composites. Similarly, inspection of composites in industry does not offer this defect information for inversion practices.

Step thermography displayed better defect definition of actual defect shape, while square-pulse thermography offers similar defect detectability to step thermography for a lower energy input and relatively lower surface temperature.

The thermal signal in thermography is well-known to be weak and requires a level of pre- or post-processing. Popular processing algorithms in literature were reviewed for transient thermography. The wavelet transform, principal component thermography and multiscale retinex displayed best overall results of the sub-surface defects. A processing graphical user interface containing the reviewed processing methods and their implementation can be found here: http://tinyurl.com/pto25n7.

The samples taken from industry in this case include small inclusions and resin variabilities which are detectable using the transient methods and the applied image processing methods. These flaws definitely do not represent large inclusions or high thermal resistances, such as flat-bottom holes.

Further studies should investigate the application of transient thermography in other engineering fields and materials. An investigation to define the limitations of transient thermography will be beneficial. The defect detectable limit should also be evaluated for smaller and thinner inclusions made from a variety of materials.

Acknowledgements
The research was funded by Armscor, South Africa and the industrial samples were provided by AAT Composites, Somerset West, South Africa.

References