Optimized temporal excitation profiles in active thermography

Udo Netzelmann

Fraunhofer-Institute for Nondestructive Testing
University, Bldg. 37, 66123 Saarbrücken, Germany

The thermal response of opaque coatings after heating with pulses of finite duration is analyzed theoretically with respect to detection of small variations of the coating thickness. Rectangular shaped heating pulses and step pulses with exponential decay are considered. The investigation is based on existing analytical solutions for step-function heating and for delta-pulse heating. For the exponentially decaying pulse, a numerical convolution is performed. For the rectangular pulse, the best sensitivity for thickness variations (thickness contrast) is generally obtained 0.2 to 0.9 Fourier numbers after the end of the pulse. A good selection for the pulse length is 0.5 to 1.5 Fourier numbers of the coating. For the exponentially decaying pulse, the maximum thickness contrast is smaller than for the rectangular pulse and easily hidden by disturbing radiation. Experimental realization of rectangular short pulses is approximately possible by switched flash lamps.

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Control of the thickness of coatings is an important task in many industrial fields. Thermal testing techniques are attractive due to their non-contact operation and large-field imaging capability.

Pulsed thermography often uses intense light sources like flash lamps or halogen lamps to generate transient heating of the test objects. A limiting case of the temporal heating profile is the delta-function like heating. For this kind of excitation, many studies (analytical and numerical) exist that analyze the thermal response of coatings, thermal resistances and local defects /1,2,3/. Another limiting case is step-function heating, that was also studied in literature /4,5/. Real flash lights produce a heating pulse with short rise-time and a long exponential decay. Shutter switched halogen light sources are generating light pulses of finite duration with a roughly rectangular shape. New high power diode laser sources are available, that allow arbitrary modulation of the excitation. Recently, a pulsed flash lamp with switchable pulse length was used for thermographic thickness characterization of thin coatings /6/. In the literature, much work has been done to describe the thermal response of such finite duration excitation analytically /7,8/. In this contribution, some further analysis is given with respect to optimized thermal contrast from thickness variations of coatings exposed to such finite duration heating pulses.

Theoretical model

One-dimensional heat propagation in an opaque coating with a thickness $d$ on a thermally thick substrate is considered (Fig. 1). The heat flow by convection at the surface is neglected.

Rectangular shape heating pulse

The surface temperature response for step-function heating, $T_s(0,t)$, can be obtained from an analytical solution in /3/:
Here, \( I_0 \) is the absorbed energy density, \( d \) is the coating thickness, \( \alpha_1 \) is the thermal diffusivity of the coating, \( \lambda_1 \) the thermal conductivity of the coating, \( \varepsilon_1 \) and \( \varepsilon_2 \) are the effusivities of coating and substrate, respectively.

The response for a rectangular pulse with a length of \( t_p \) is then given by \( T_p(0,t) = T_s(0,t) - T_s(0,t-t_p) \) (for \( t > t_p \)).

A question of practical importance in active thermography is how to select the pulse length \( t_p \) to obtain an optimized sensitivity for detection of small thickness variations of the coating, and at which time the temperature contrast from such varying coating thickness can be detected best (Fig. 2).

Fig. 2: Typical surface temperature response to a rectangular heating pulse with a variation of the coating thickness of \( \pm 5\% \) for a thermal reflection coefficient of \( R = -0.5 \). The time is expressed dimensionless in Fourier numbers \( F_o = \frac{\alpha_1 t}{d^2} \).

This is accessible by considering \( \frac{\partial T_r}{\partial d} \), a quantity that in the following is denoted as "thickness contrast". For the rectangular shape pulse one obtains:

\[
\frac{\partial T_r}{\partial d}(0,t_p) = \frac{\partial T_r}{\partial d}(t_{p} - t_{p}), t \leq t_p \\
\quad= \frac{\partial T_r}{\partial d}(t_{p} - t_{p} - t), t > t_p
\]

with

\[
\frac{\partial T_r}{\partial d}(0,t_p) = -4 \frac{\lambda_1}{\alpha_1} \sum_{n=1}^{\infty} \left( \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \varepsilon_2} \right)^{2n} \text{erfc} \left( \frac{n}{\sqrt{F_0}} \right).
\]

Here, the time is expressed in the dimensionless Fourier number \( F_0 = \frac{\alpha_1 t}{d^2} \) of the coating, in order to achieve more general results.

For the following calculations, the temperature contrast, the thickness contrast and their maxima and the times of occurrence of the maxima were computed by a Mathematica program. In Fig. 3, some examples for the maximum thickness contrast as a function of the pulse length \( F_0 = \frac{\alpha_1 t}{d^2} \) are shown for different thermal reflection coefficients \( R = (\varepsilon_1 - \varepsilon_2)/(\varepsilon_1 + \varepsilon_2) \).

The absolute of the maximum contrast increases monotonously with pulse length, but reaches saturation for negative reflection coefficients for \( F_0 > 2 \).

Fig. 3: Maximum thickness contrast as a function of the pulse length for a rectangular heating pulse and thermal reflection coefficients from \( R = -0.9 \) to \( +0.9 \).

Exponentially decaying heating pulse

In this case, one can start with the well known result for the response to delta pulse heating /3/:

\[
T_r(0,t) = \frac{Q_0}{2 \sqrt{\pi E_0 c_1 d^2}} \left( 1 + 2 \sum_{n=1}^{\infty} \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \varepsilon_2} \text{exp} \left( -\frac{n^2 d}{\alpha_1 t} \right) \right),
\]

where \( Q_0 \) is the absorbed energy. The thickness contrast, expressed in Fourier-numbers, is given by:

\[
\frac{\partial T_r}{\partial d}(0,t_p) = -2 \frac{Q_0}{\sqrt{\pi \rho_1 c_1 d^2} F_0} \sum_{n=1}^{\infty} \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \varepsilon_2} \text{exp} \left( -\frac{n^2 d}{F_0} \right).
\]

Here \( \rho_1 \) is the density, \( c_1 \) the specific heat capacity of the coating. This has to be convoluted with the excitation flash pulse shape. A typical shape for a flash lamp (Fig. 1) is in good approximation given by:

\[
\text{H}(t_p) = H_0 \left( \frac{t_p}{\tau_s} \right)^2 \text{exp} \left( -\frac{t_p}{\tau_s} \right),
\]

where \( \tau_s \) is the rise time and \( \tau_f \) the fall time of the flash intensity. As typical values are \( \tau_s = 0.15 \text{ ms}, \tau_f = 5 \text{ ms}, \) with \( \tau_f << \tau_0 \) the signal is in the following further approximated by:

\[
H(t_p) = \begin{cases} 
0, & \text{if } 0 < t_p < \tau_s \\
H_0 \text{exp} \left( -\frac{t_p}{\tau_s} \right), & \text{if } t_p \geq \tau_s
\end{cases}
\]
The thermal contrast response of the exponentially decaying pulse is then given by the convolution with excitation flash pulse shape $H(\tau)$:

$$\frac{\partial T_{\text{flash}}(0,t)}{\partial t} = \int H(\tau) \frac{\partial T_{\text{e}}}{\partial \tau}(1-\tau) \, d\tau$$  \hspace{1cm} (8)

Comparison of rectangular and exponentially decaying pulses

The behavior of the maximum of the thickness contrast as a function of the pulse length $F_0=\alpha \tau_f/d^2$ of the exponential pulse is qualitatively similar to that of the rectangular pulse shown in Fig. 3. The time, when the maximum of thickness contrast occurs shows significant differences (Figs. 4 and 5). For very short pulses of both types, the optimum observation time is about 0.6 to 0.9 Fo-numbers. The contrast maximum for the rectangular pulse occurs always after the end of the pulse. For large pulse lengths it lies about 0.2 to 0.5 units after the end of the pulse.

For the exponential pulse (Fig. 5), with increasing pulse fall-time the thickness contrast maximum occurs earlier and earlier with respect to the fall-time. Very often it lies within the high intensity part of the flash (more than 5% of the peak intensity), in particular for negative reflection coefficients. In the experiment, the point of best thickness contrast may be disturbed by interference from flash lamp radiation.

Another question is the efficiency of contrast generation. If one plots the maximum thickness contrast normalized to the total pulse energy, one can see that a rectangular pulse of finite duration allows better use of the heating energy than an exponential pulse (Fig. 6). For both pulse shapes, the efficiency is slowly decreasing with the pulse length. Positive reflection coefficients give a better yield than negative.

If one compares both pulse shapes for a fixed peak surface temperature (relevant for possible damage of the sample), the efficiency for small Fo-numbers generally increases with increasing pulse length and runs into saturation for large Fo-numbers (Fig. 7). For $R=+0.5$, the efficiency of the rectangular pulse has a slight maximum at $F_0=1.1$. 
Fig. 7: Maximum thickness contrast normalized to the maximum occurring surface temperature for rectangular and exponential heating pulses for two selected thermal reflection coefficients R.

**Experimental realization**

A good compromise between energy efficiency, temperature loading and size of the thickness contrast is to use a rectangular heating pulse with a length of about one Fo-number. For short absolute times, a way to realize this approximately may be a thyristor switched flash lamps which fast cut-off time (Fig. 8). Cut-off times of less than 50 µs are achievable.

Fig. 8: Flash intensity as a function of time for two pulse length settings (180 µs and 590 µs) of a thyristor switched flash lamp as measured by a fast photodiode.

In general, when working in the time-domain an approach to achieve a good sensitivity for detecting small thickness variations in coatings is to pump sufficient heating energy into the system and to switch off heating as fast as possible. Similar considerations should apply for detection of small sub-surface defects or onset of coating delamination.

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**References**