Pulsed thermography in multiple infrared spectral bands

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Abstract. Spectrally resolved active thermography by flash pulse excitation was performed in four sub-bands of a mid-wave infrared camera using spectral filtering and in the full long-wave band of a second infrared camera. On zirconia thermal barrier coatings on steel and PVC blocks, spectrally dependent decay rates of the thermal contrast were found. The observed behaviour can be explained by the infrared spectra of the specimens.

1. Introduction

Active thermography using pulsed or periodic excitation has become an important tool for non-destructive testing with applications in industry. Typical tasks are defect detection in components or quantitative thickness determination of coatings. Today, infrared detectors with information averaged over one spectral band are employed. The optical properties of the test objects in the visible and in particular in the thermal infrared were considered in early models for photothermal radiometry [1,2] but the effects were usually not much considered, with some exceptions in biological applications [3,4] and in coating characterization [5]. Infrared single band point detectors were employed in this work. On the other hand, it is known that certain coatings, for example ceramic thermal barrier coatings for turbine blades, have a very different infrared absorption in the mid-wave IR and in the long-wave IR. Moreover, spectra in the mid-wave band are dependent on coating aging [6]. The effect of infrared translucence of thermal barrier coatings and its consequence for thickness determination was discussed in [7]. Polymers often have strong spectral signatures in the infrared, which may lead to errors in defect depth characterization. In this work, we report about first attempts to take profit of spectral information in active thermography.

2. Experimental

Thermally sprayed Yttrium stabilized zirconia thermal barrier coatings with slight variations of the spraying conditions and a thickness of 1.5-1.8 mm on a thermally thick steel substrate and thick polymer specimens were investigated with flash light induced transient heating.

A Cedip 480 M mid-wave infrared camera (3.6-5 µm) equipped with four spectral filters, each with about 0.4 µm bandwidth, was used for the experiments. The filter transmission curves are shown in Fig. 1. The camera is temperature calibrated for measurements with the filters, which are mounted on a rotatable filter wheel. The heating technique is pulsed flash heating using two lamps. Each pulsed experiment has to be repeated four times to obtain the full spectral information. The stability of the equipment turned out to be better than the required accuracy. Additional experiments were performed using a VarioCam HR infrared camera for the long-wave infrared band (7.5-14 µm). An averaged
image before flash heating was subtracted from the recorded image sequences. The radiation contrast response curves were obtained from data averaged over surface areas of each specimen in order to improve signal/noise. Then, the radiation contrast decay curves were compared between the spectral bands. For this purpose, the decay curves were plotted together in a log-log diagram.

![Graph](image)

**Figure 1.** Transmission spectra of the four filters used for the pulsed thermography experiments

### 3. Results and discussion

For the zirconia specimens, the results of the full mid-wave range (without filters) compared to the full long-wave range show large differences in the absolute apparent temperatures, in the slope of the decay curves and in the position of the bending points due to substrate influence.

Fig. 2 shows thermal decay curves in the mid-wave sub-bands for a selected zirconia sample. The ceramic coatings are thick enough that until a time of about 1 s no slope change due to the metal substrate is observed. The logarithmic slope $s = d(\ln(\Delta T))/d(\ln(t))$ was analysed for the time regime of 0.1 to 1 s. It should be $s = -0.5$ for a half-space surface absorber and emitter and between 0 and -0.5 for an optically and/or infrared transparent sample [3]. In Fig. 2, right, these slopes $s$ are shown for the four spectral ranges.

![Graph](image)

**Figure 2.** Thermal decay curves (apparent temperature contrast) after flash excitation of the zirconia coated specimen #80 for four different spectral bands (left). Evaluated logarithmic slope for the time regime 0.1 to 1 s (right)
For the PVC sample, the decay curves are shown in Fig. 3. The spectral dependence of the slope is even larger and ranges from -0.5 in the shortest wavelength sub-band to -0.41 in the longest wavelength sub-band.

![Figure 3](image1.png)

**Figure 3.** Thermal decay curves (apparent temperature contrast) after flash excitation of the PVC specimen for four different spectral bands (left). Evaluated logarithmic slope for the time regime 0.1 to 1 s (right)

Before discussing these results further, we refer to the infrared reflection spectra of the specimens as measured by an Exoscan FTIR spectrometer (A2Technologies). In Fig. 4, the spectra of the zirconia samples are shown along with an indication of the position of the spectral bands of the filters. For ceramic coatings, the infrared absorption coefficient behaves roughly inverse to the infrared reflectivity [8], therefore the lower reflectivity in the 3.6-4 µm range corresponds to a higher IR absorption coefficient. This means, that the radiation comes more from the surface whereas in the other bands there are more contributions from deeper layers. In the experiment, this leads to different decay slopes. From the spectra in Fig. 4 it becomes obvious that the difference between the mid-wave band and the long-wave band is even more pronounced. Qualitatively similar, but steeper in the mid-wave band is the spectrum of PVC (Fig. 5), corresponding to the larger variation of the slope found in the experiment.

![Figure 4](image2.png)

**Figure 4.** Infrared reflection spectra from the investigated zirconia coated specimens with indication of the four spectral bands.
A thermal diffusion model was set up taking account for the optical extinction behavior in the visible and the infrared emission and re-absorption of radiation from the depth of the sample. In addition to published work, the thermal pulse reflection at a coating-substrate interface was included. Due to uncertainties of optical material parameters and approximations about optical reflection at the coating-substrate interface, the experimental results are up to now only in qualitative accordance with the model. Details will be reported elsewhere.

4. Conclusion
Spectral effects are clearly detectable in infrared semi-transparent specimens. The spectrally resolved information may help to obtain higher accuracy in non-destructive thickness determination of translucent coatings and to reduce the calibration effort for production testing systems. Using present infrared cameras, the effort for changing the filters, for repetitive excitation and for the correction of effects caused by the non-simultaneous measurement is high. Therefore, infrared cameras with multi-color or multi-band capability will be a significant progress for certain non-destructive testing applications.

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