NDE2002 predict. assure. improve.
National Seminar of ISNT
Chennai, 5. – 7. 12. 2002
www.nde2002.org

Pulsed Thermal Methods for Materials Characterization

U. Netzelmann, R. Heeg and G. Walle

Fraunhofer-Institute for Nondestructive Testing, Saarbruecken, Germany

Abstract: Dynamic thermographic techniques with different temporal excitation schemes are discussed and compared. A key application is the thickness measurement of industrial ceramic coatings on curved surfaces. Rules for optimised excitation profiles can be deduced from analytical calculations. Non-optical excitation by hot air, electromagnetic waves or ultrasound may help to avoid the problem of optical absorptivity for some tasks and provides defect-selective imaging.

Contact information:
Dr. U. Netzelmann, Fraunhofer IZFP, University, Bldg. 37, 66123 Saarbruecken, Germany
Tel: +49 681 9302 3873, Fax: +49 681 9320 5920, udo.netzelmann@izfp.fraunhofer.de

Introduction

Active, dynamic thermography is a field that is in rapid development due to its attractive features in applications, namely non-contact operation, large field imaging and high speed testing. A pulsed thermographic testing system comprises an excitation source with a certain temporal excitation profile, a thermal diffusion process in the test object and a detection unit [1]. If the heat flow into the depth of a material is disturbed by interfaces or defects, a temperature change will result, that can be detected at the surface of the test object. The detector is usually an IR camera. There are recent developments in infrared camera technology that make this technique more and more interesting for applications:

- A significant increase in sensitivity down to the mK range in quantum well IR photodetectors (QWIP)
- Focal plane arrays up to 640 x 480 pixels image resolution
- Simplified cooling by using Sterling coolers or the use of microbolometers

In this contribution, some aspects of the different variants of dynamic thermography are discussed and recent developments in defect selective excitation are shown.

Coating thickness measurements

A field of applications of pulsed thermal techniques with high potential for industrial quality control is the large-field measurement of coating thickness. Fig. 1 shows a plot of typical response times of the contrast from the coating-substrate interface for pulsed (a delta-pulse shape is assumed) heating. The beginning of contrast occurs usually at a time of about $t_{beg} = 0.25\ d^2/\alpha$, where d is the coating thickness and α is its thermal diffusivity. It is obvious, that due to the very different thermal properties and due to the quadratic dependence of t_{beg} on d, thin metallic coating reach their contrast

maximum at times below 10 ms, whereas thicker polymer coatings will need several seconds to show full contrast. In the first case, high-speed IR cameras with frame rates of 1000 frames/s are required.

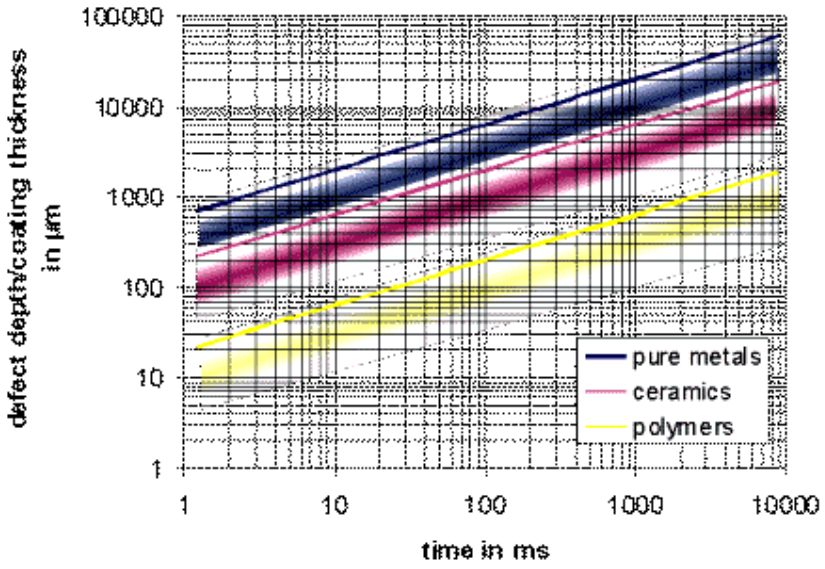

Fig. 1: The relation between coating thickness and the time for begin of thermographic contrast (thin lines) and expectation range for maximum contrast (broad bands) for different material classes. Top: pure metals, middle: ceramics, bottom: polymers.

Present important applications, that have led to first automated industrial testing systems, are the measurement of the thickness of zirconia based ceramic turbine blade coatings as used as thermal barrier coatings and corrosion resistant coatings [2,3,4]. It is a unique advantage of thermographic thickness measurement that it does not critically depend on a small curvature of the coated surface.

Temporal excitation profiles

A high accuracy of coating thickness measurement is desired, often in presence of variations of thermal and optical properties of such coatings. This problem is not satisfactory solved up to now. One aspect is to use optimised pulse shapes that are very sensitive to small variations of coating thickness. Here, theoretical modelling [5] helps to predict optimum conditions for heating without regarding a specific application. Two pulse excitation forms, that are quite frequently in use are rectangular and exponentially decaying heating (Fig. 2). An analysis for surface-absorbing coatings in 1D-geometry shows, that for exponential heating the interesting parts of the contrast are occurring during the decay of the illumination phase. If a rectangular pulse is used, the contrast output is usually somewhat better. If the heating source has a short switch-off time constant, observation of the contrast maximum occurs always after switch-off. Such pulses can practically be realised by thyristor switched flash tubes [6].

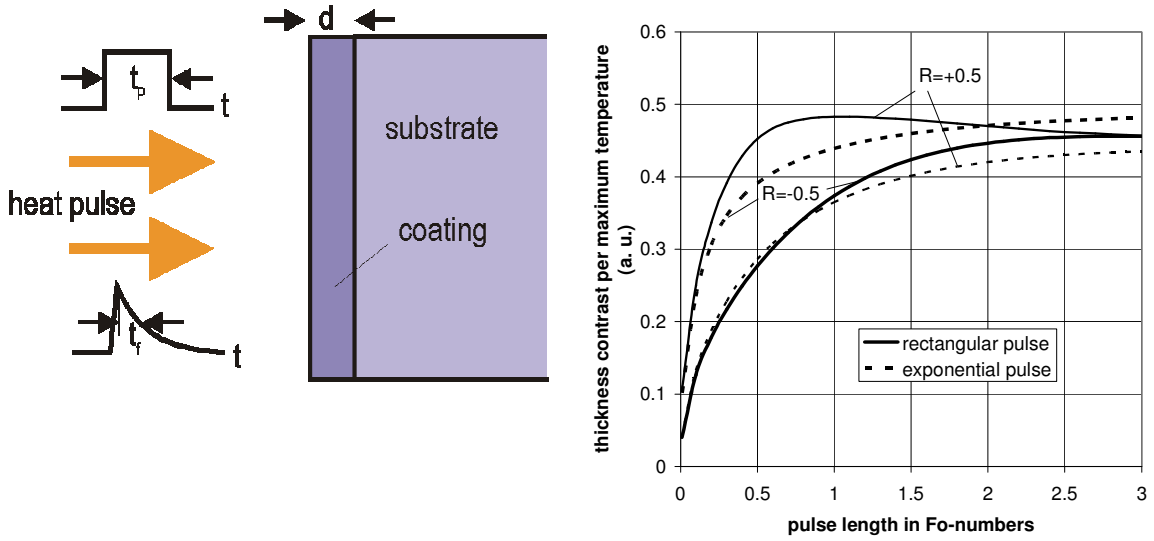

Fig. 2: Comparison between rectangular and exponential pulsed heating for thermographic thickness measurement. Left: Scheme. Right: Calculated thickness contrast per maximum temperature as a function of the pulse length (t_p or t_F, respectively) in Fourier numbers $Fo=\alpha t/d^2$. The parameter R is the thermal reflection coefficient between coating and substrate [6].

An alternative to pulsed heating is step-heating [7], where a heating source is switched on at t=0 and is then heating with constant intensity. Here, the absolute value of the contrast can be expanded with time until lateral heat flow dominates and recognition of local defects is no longer improved [8]. A general problem is that heating and observation have to be performed at the same time, which may cause interference due to spurious long-wave radiation from the heating source. A long heating phase followed by a fast switch-off of heating may be advantageous in such cases.

A variant of dynamic thermography which uses a “built-in” normalisation for suppression of emissivity contrast and contrast due to inhomogeneous optical illumination is lock-in thermography [9]. By selecting a certain thermal diffusion length via the sinusoidal modulation frequency, the technique can be made very sensitive to defects in a certain depth of a material. It is easy to improve the signal/noise ratio by collecting the signal over more and more modulation cycles. Of course, this is at cost of the total measurement time.

There can be no general recommendation for one of these thermographic variants, as the external requirements will be different from application to application. Table 1 tries to give a first orientation.

An alternative to the classical excitation schemes discussed in Table 1 are dedicated excitation signals that take profit of the possibilities of fast signal processing offered by digital signal processors. For example, cross-correlation techniques [10] can be implemented easily and require only a short signal processing time. A sensor with purely digital signal processing was realised based on a single element IR detector [11]. The sensor shown in Fig. 3 was designed to measure the thickness of polymer coatings in the 10-100 µm regime. The cross-correlation technique allows one to multiply the peak pulse intensity obtainable from a limited power cw excitation source.

Another approach uses two or more superimposed sinusoidal excitation frequencies in the excitation signal [12].

	Pulsed thermography	Step heating thermography	Lock-In thermography
Measurement speed	fast	medium	low
Normalisation/ artefact suppression	No standard, but various approaches are used	No standard approach	built-in (phase image)
Total testing energy	Fixed, limited	Proportional to time, limited	Proportional to time
Penetration depth	Preferably low (for flash pulses)	medium	large
Unknown defect depth	favourable	favourable	Optimisation of modulation frequency required
Heating and observation phase separated	yes	No (for switch on) Yes (for switch off)	no
Maximum transient temperature rise	high	low	low

Table 1: Comparison of some aspects of three variants of dynamic thermography

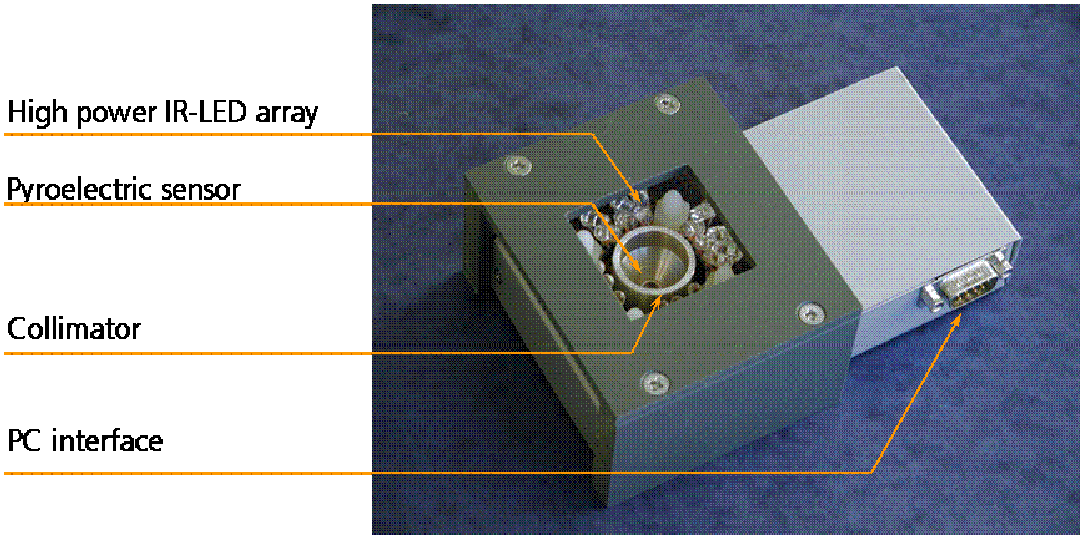

Fig 3: Photograph of a prototype of a single-element thermal pulse sensor using a cross-correlation technique and excitation by a high-power light emitting diode array [11]

Non-optical excitation

Non-optical excitation techniques can be used to avoid specific disadvantages of the optical illumination. Fan thermography (using a hot air stream) reduces the problem of optical absorptivity in critical cases and is a comparably well-priced method [1]. Electromagnetic heating based on eddy current losses can be used to detect cracks in metallic components. Microwave heating will heat moisture nests inside materials and can thereby lead to defect-selective heating providing good contrast.

Ultrasonic heating [13] relies on dissipative phenomena and occurs at regions of internal friction in the volume and in particular at cracks. A test object is exposed to high intensity ultrasound (typically at 20 kHz) with pulses of some 10 ms to some s length. The heating of cracks close to the surface can be observed during heating (Fig. 4). Detailed studies on the signal generation processes and search for application fields are presently ongoing.

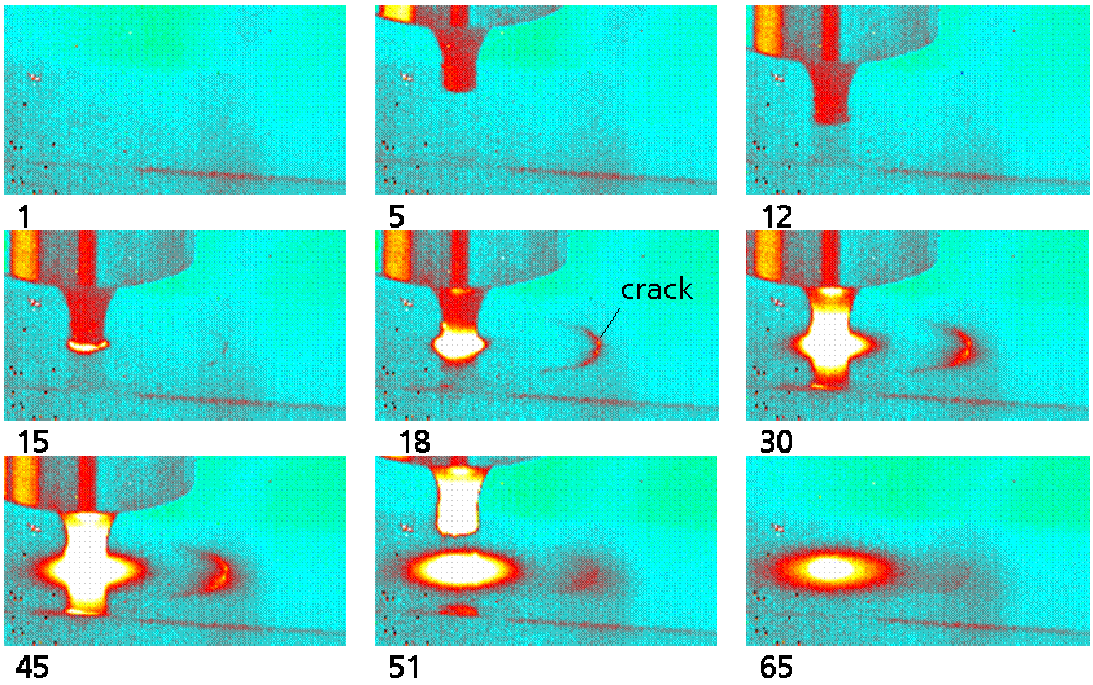

Fig. 4: Thermographic image sequence of an ultrasonic excitation of a crack in steel using a 20 kHz ultrasound sonotrode (appearing in the left part). The numbers represent the elapsed testing time in units of 100 ms.

References

[1] U. Netzelmann, J. Hoffmann, and N. Meyendorf, 'Thermal Techniques for Coating Characterization', in: "Detection and Characterization of Early Stages of Damage in Aerospace materials", Final Report DARPA-MURI (Center for Materials Diagnostics, University of Dayton 2002) 243

[2] L. Fabbri, M. Oksanen (eds.), et al., 'Characterisation of plasma-sprayed coatings using NDE techniques', INSIGHT **39**, 887 (1997)

[3] F. Cernuschi, U. Netzelmann and K. J. Pohl, "Nondestructive integrity characterisation and assessment of gas turbine coatings within the COST-501 program", Proc. 6th Liege Conference on Materials for Advanced Power Engineering, Liege, Belgium 5.-7.10.98, Schriften des Forschungszentrums Jülich: Reihe Energietechnik, Band 5,3 (Forschungszentrum Jülich 1998) 1587

[4] C. Florin, 'A new and reliable method for non-destructive and non-contact testing of thermal spray coatings', INSIGHT **42** No. 9, 606 (2000)

[5] S. Lau, D. Almond, and P. Patel, "Transient thermal wave techniques for the evaluation of surface coatings", J. Phys. D: Appl. Phys. 24, 428 (1991)

[6] U. Netzelmann, 'Optimized temporal excitation profiles in active thermography', Analytical Sciences (Japan) 17 (2001), s432

[7] J. W. Maclachlan Spicer, W. D. Kerns, L. C. Aamodt, and J. C. Murphy, "Time-Resolved Infrared Radiometry for Characterization of structured materials", in: Photoacoustic and Photothermal Phenomena II, J. C. Murphy and J. W. Maclachlan Spicer (eds.) (Springer-Verlag, Heidelberg 1990), 55

[8] L. D. Favro, P. K. Kuo, and R. L. Thomas, "Synchronous thermal wave imaging", Progress in Natural Science (China) 6, S-135 (1996)

[9] G. Busse, D. Wu, D., and W. Karpen, "Thermal wave imaging with phase sensitive modulated thermography", J. Appl. Phys. Vol. **71** (1992), pp. 3962-3965

[10] G. F. Kirkbright and R. M. Miller, 'Cross-Correlation Techniques for Signal Recovery in Thermal Wave Imaging', Analytical Chemistry **55**, 502 (1983)

[11] R. Heeg, Studienarbeit, Fraunhofer IZFP and Universität des Saarlandes, Saarbrücken 2002

[12] T. Mangold, Ph. D. Thesis, Universität des Saarlandes 2000

[13] R. B. Mignogna, R. E. Green, J. C. Duke, E. G. Henneke, and K. L. Reifsnider, 'Thermographic investigation of high-power ultrasonic heating in materials', Ultrasonics, 159 (1981)