A Multi-Parameter Probability of Detection (POD) Model for Flash Thermography

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Abstract

In most cases where a POD is calculated based on continuous data obtained by active thermography, the signal-to-noise ratio (SNR) of the signal, the difference of the defect signal to the background or the absolute signal is analysed as a function of the aspect ratio (ratio of the size of a defect to its overage), although a distinct linear relationship on a linear or logarithmic scale could not be satisfactorily shown and is also not expected. Therefore, a multi-parameter probability of detection (POD) model was developed, where an â versus a continuous signal analysis was based on the linear relationship between the SNR and a multi-parameter a. This POD model is based on data which were recorded within a flash thermography round robin test with nine participants. Metal test specimens with flat bottom holes (FBHs) were analysed by calculating the SNR of the defect signatures in the thermograms as well as in the phase images as a function of defect parameters. The linear relationship of the experimental data to the multi-parameter a was verified by comparison to data obtained from an analytical model that is considering lateral thermal heat diffusion as well as to data obtained by numerical simulation. The resulting POD curves for the thermograms and phase images give an estimation for the detectability of the FBHs with known geometry in steel using different equipment and obtained by different participants. By comparing the SNRs of FBHs with similar geometries, this POD model was transferred to aluminium and copper as well.

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A MULTI-PARAMETER PROBABILITY OF DETECTION (POD) MODEL FOR FLASH THERMOGRAPHY

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Aim and implementation of the POD of flash thermography

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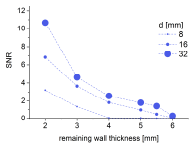
DIN

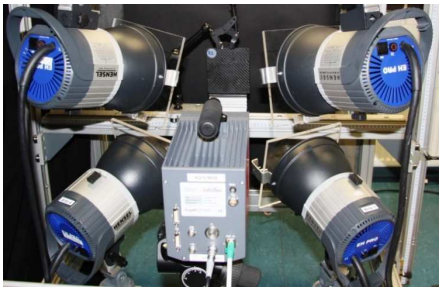
- Performance of a round robin test for the approval of a draft national standard on flash thermography
- Comparability of data obtained with different equipment and analysed by different participants
- Investigations at different materials: steel, aluminium, copper. The same set of test specimens was sent to each participant one after the other.
- Test instructions and test protocols were predefined
- Data were collected and analysed at BAM
- A multiparameter POD model was developed and applied to the data sets of each partner

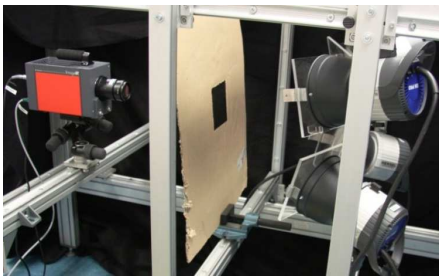


N. Rothbart, C. Maierhofer, M. Godlammer et al; QIRT Journal 2016,
http://dx.doi.org/10.1080/17686733.2016.1229246

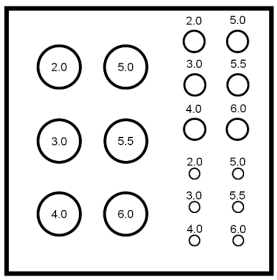
Participants and used equipment

- **No. of participants:** 9
- **No. of test specimens:** 3 (16)
- **Used equipment:**
  - Flash lamps: 3 to 24 kJ
  - IR-cameras: 1 x microbol., 8 x InSb
  - Measurement conf.: reflection, transmission
  - Frame rate: 50 to 330 Hz
  - Data analysis: thermograms, phase images, no. of detected defects, SNR, size
- **Preparation of samples:**
  - Graphite spray for metals

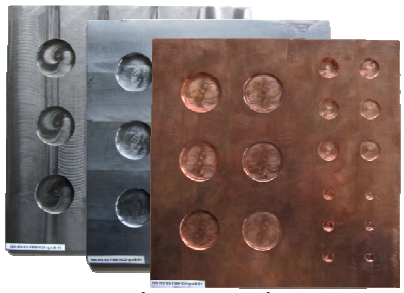




Test specimens with flat bottom holes (FBHs) Diameters: 8, 16 and 32 mm; depths: 2 to 6 mm



Thickness of plates: 7.5 mm
Numbers give the remaining wall thicknesses



stainless steel
aluminum
copper

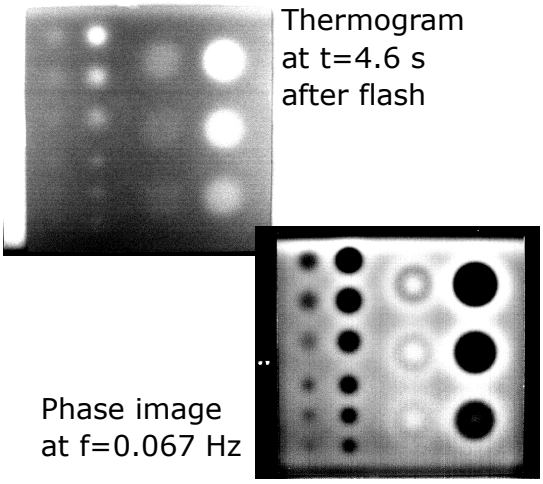
Material	Diffusivity α in 10^{-5} m^2/s
steel 1.4301 X5CrNi18-10	0.37 ± 0.02
aluminium 3.3206 AlMgSi0.5	5.0 ± 0.2
copper CW004A	9.8 ± 0.4

Determined experimentally from transmission measurements

Data analysis for the determination of detectability of FBHs

Large steel test specimen

- Subtraction of thermogram recorded before the flash (zero image) from the whole sequence
- Application of Pulse Phase Thermography (PPT) to the sequence starting with the first image directly after the flash
- Determination of detectability of FBHs in selected thermograms and selected phase images by subjective decision of the test personnel

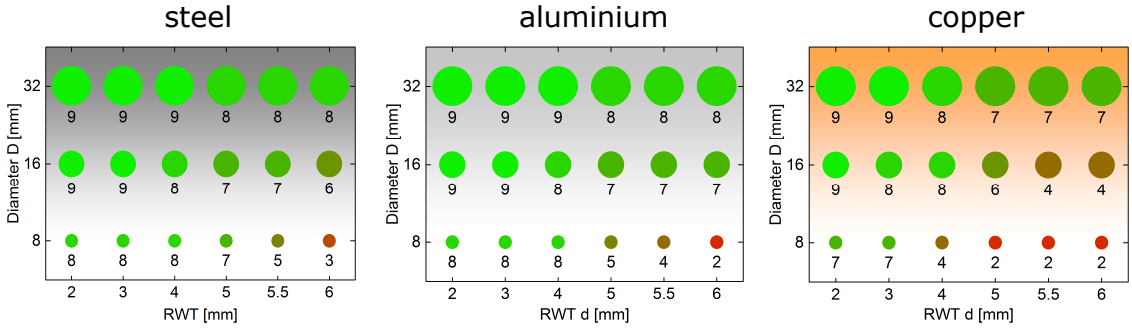


Thermogram at t=4.6 s after flash

Phase image at f=0.067 Hz

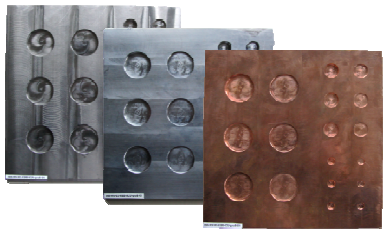
Detectability* of FBHs with larger diameters

*in thermograms or phase images

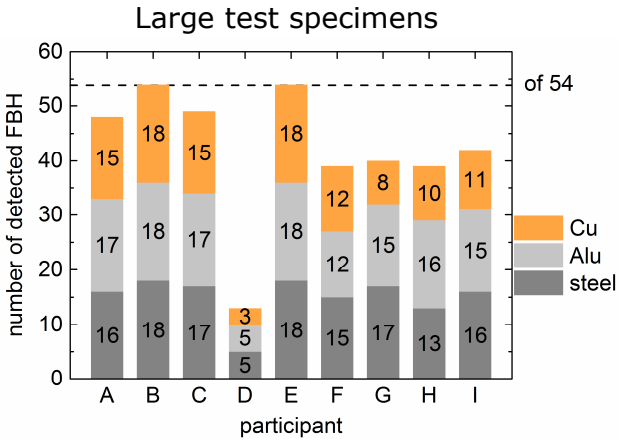


- Deeper holes could be detected less often due to limited penetration depth
- Smaller diameters could be detected less often due to lateral diffusivity

Number of detected FBHs for each participant and each material in the phase images



By some of the participants, less FBHs could be detected especially in Cu.



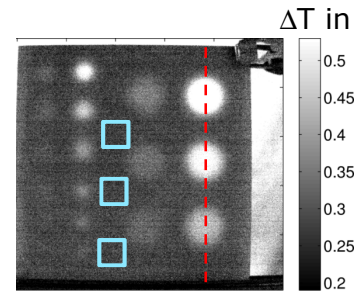
Determination of signal-to-noise ratio

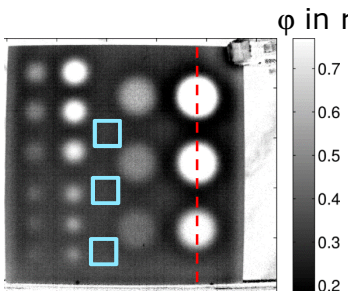
$$SNR_T = \frac{\Delta(\Delta T)}{\sigma_T} \qquad SNR_\varphi = \frac{\Delta\varphi}{\sigma_\varphi}$$

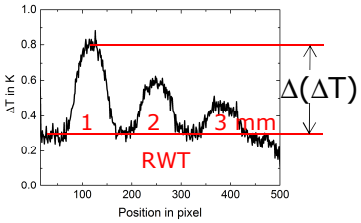
Δ(ΔT) and Δφ are determined from line scans across the defects

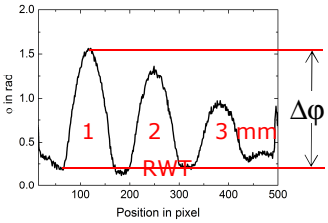
σ is the standard deviation of e.g. 100 pixels at three positions in sound areas

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$



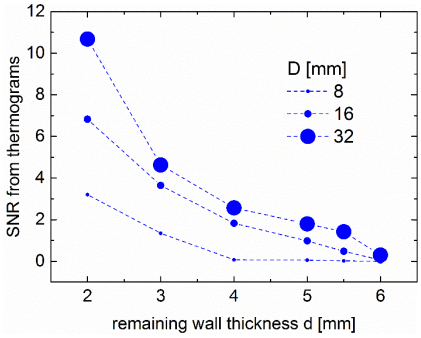






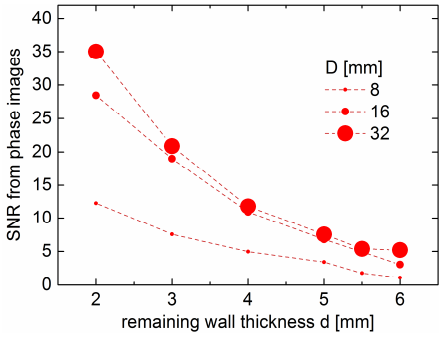
SNR in thermograms and phase images, large steel test specimen, as a function of RWT

SNR thermograms



- SNR was averaged over all participants
- SNR decreases with increasing remaining wall thickness

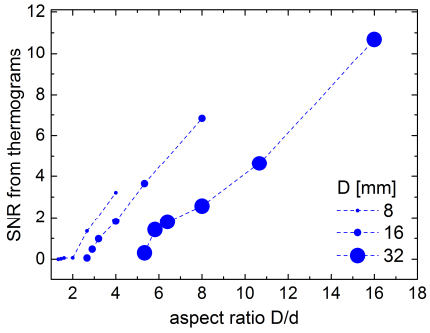
SNR phase images



- SNR decreases with decreasing diameter
- In all cases, the SNR is higher in the phase images

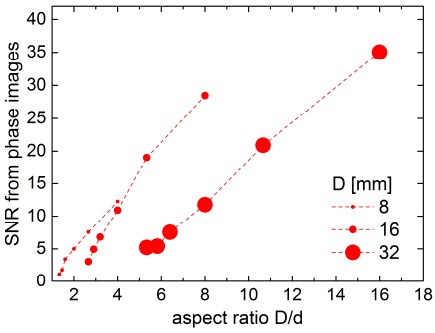
SNR in thermograms and phase images, large steel test specimen, as a function of aspect ratio

SNR thermograms



- For similar aspect ratios, FBHs with a smaller diameter have a higher SNR

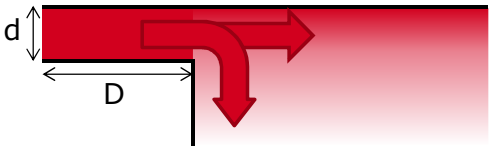
SNR phase images



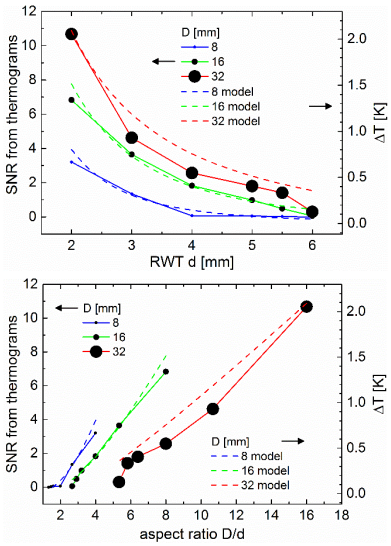
- There is nearly a linear relationship between SNR and aspect ratio, but only for a fixed diameter

Analytical model for the consideration of 3D heat diffusion around defects

$$\Delta T(0,t) = \frac{2q_0}{\sqrt{\pi\rho c\lambda_z t}}\left[\sum_{n=1}^{\infty} R^n e^{-\frac{(nd)^2}{\alpha_z t}}\right]$$



*Almond DP, Pickering SG. J. of Appl. Phys. 111, 093510 (2012)



Introduction of a defect parameter

For POD analysis, a defect parameter is required which depends linearly on the measured signal:

$$\hat{a}(a) = B_0 + B_1 \cdot a + \delta$$

- No linear dependence of SNR on diameter D, defect depth d or aspect ration D/d
- Introduction of empirical defect parameters:

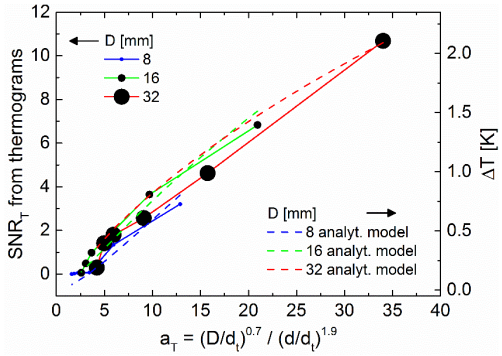
$$a_T = \frac{(D/d_t)^{0.7}}{(d/d_t)^{1.9}}$$ for thermo-grams

$$a_\varphi = \frac{(D/d_t)^{0.7}}{(d/d_t)^{1.6}}$$ for phase images

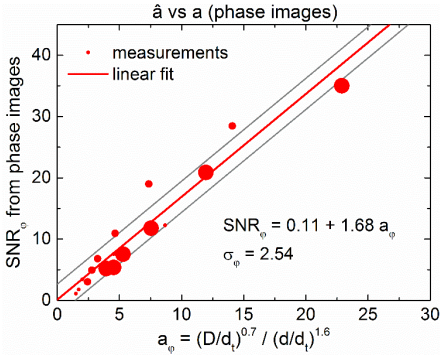
d_t: thickness of the plate

Linearization with the defect parameter
Mean values of all participants

SNR thermograms



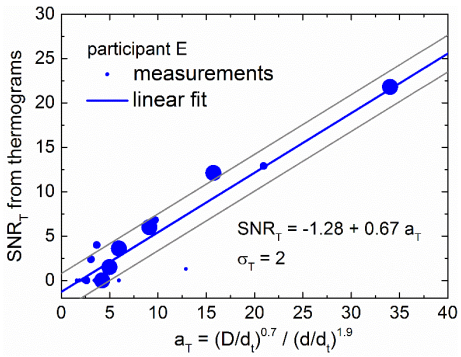
SNR phase images



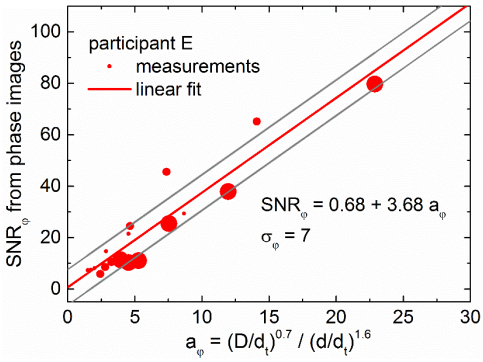
Linearization of the SNR_T values in the thermograms has a lower standard deviation as linearization of SNR_φ values in the phase images

Linearization with the defect parameter
Values of participant E

SNR thermograms



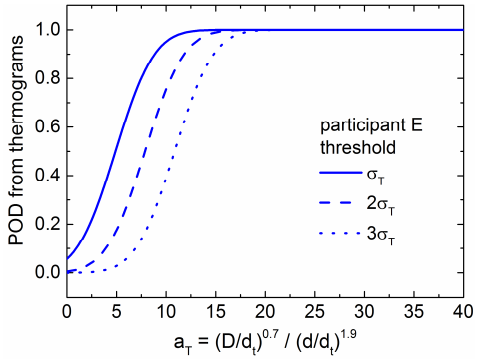
SNR phase images



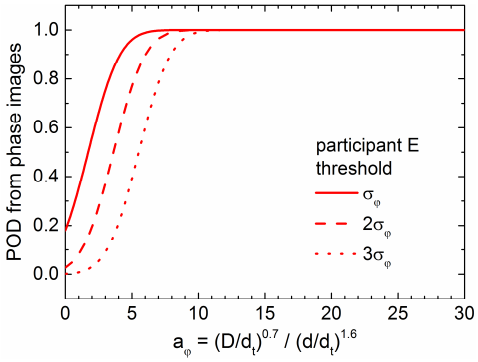
For the linearization of the data of individual participants, the standard deviation is larger. Rel. standard deviation of thermograms and phase images is similar.

POD as a function of defect parameter
Data of participant E

POD thermograms



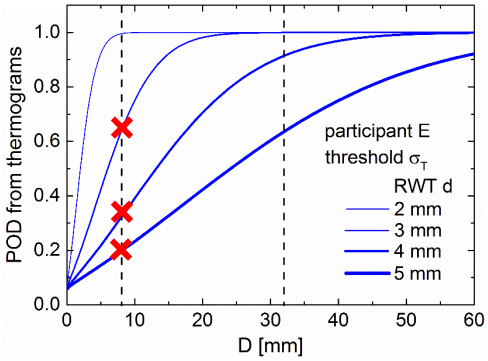
POD phase images



A direct comparison of both graphs is not possible as both defect parameters have a different meaning. How is an interpretation possible?

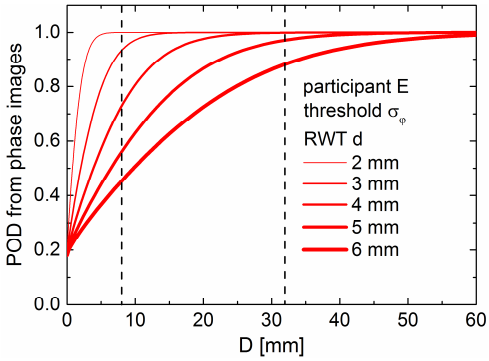
POD as a function of defect diameter
Data of participant E

POD thermograms



Crossed diameters could not be detected

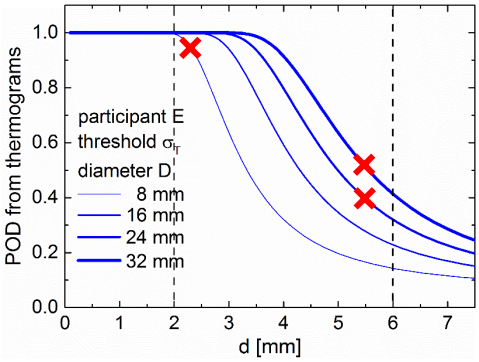
POD phase images



Within the phase images, the FBHs could be detected with higher reliability.

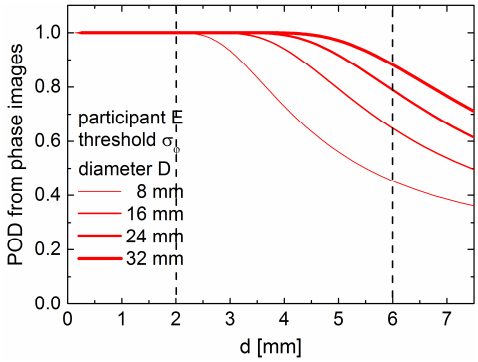
POD as a function of defect depth
Data of participant E

POD thermograms



Crossed depths could not be detected

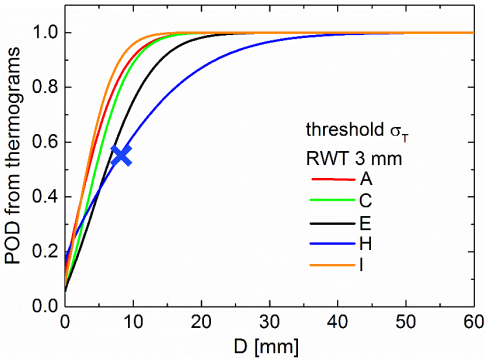
POD phase images



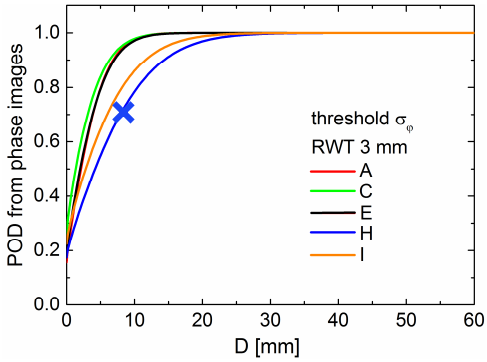
Within the phase images, the FBHs could be detected with higher reliability.

POD as a function of diameter
Comparison of POD of different participants

POD thermograms



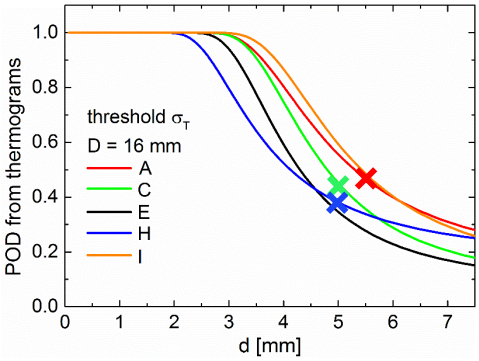
POD phase images



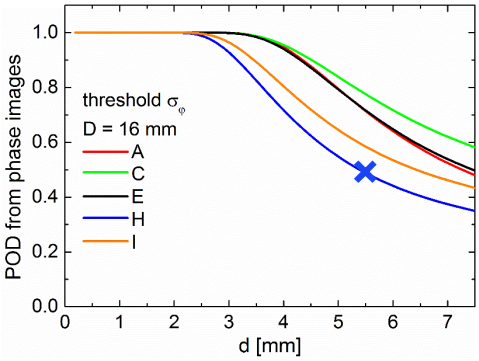
The lowest POD values in the thermograms were obtained by participants E and H, the lowest POD values in the phase images by participants H and I.

POD as a function of depth
Comparison of POD of different participants

POD thermograms



POD phase images



→ Clear influence of procedure used for the calculation of phase images
→ Standardization is required

Summary and conclusion

Detectability and SNR of FBHs

- Both is higher in steel, less in Cu due to higher diffusivity
- SNR is higher in the phase images
- SNR decreases with d and increases with D, no general unique dependence on aspect ratio
- Influence of equipment, data analysis and personnel staff is unincisive, up to three groups of participants

POD analysis

- â versus a analysis for the POD requires the introduction of a defect parameter(multi parameter appr.) for the linearization of SNR
- For interpretation, POD curves can be calculated as a function of depth or diameter separately
- If the threshold is set to the standard deviation of the linear fit, the POD curves are reflecting very well the experiments

Outlook

- More data are required for the validation of the multi-parameter
- Specification of algorithms and boundary conditions used for Pulse Phase Thermography (frame rate, start image, number of images, FFT algorithm, windowing etc)
- Comparison of different data analysis procedures
- Draft national standard on flash thermography is available:

E DIN 54184:2017-01 Non-destructive testing – Pulse thermography using optical excitation

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