



# Laser Projected Photothermal Thermography for Characterizing Hidden Defects

Erik THIEL<sup>1</sup>, Marc KREUTZBRUCK<sup>2</sup>, Mathias ZIEGLER<sup>1</sup>

<sup>1</sup> BAM Bundesanstalt für Materialforschung und -prüfung, Berlin, Germany

<sup>2</sup> Universität Stuttgart, Stuttgart, Germany

Contact e-mail: [erik.thiel@bam.de](mailto:erik.thiel@bam.de).

**Abstract.** For the last 20 years active thermography has developed into a standard method in non-destructive material testing. It has become possible to detect defects such as cracks, voids, or even material inhomogeneities. Until now, it is still difficult to quantify subsurface or hidden defects in size due to the diffusive nature of heat flow within a solid. Facing this issue, lockin thermography and other photothermal techniques have been established. They are based on exciting a sample periodically (e.g. with a halogen lamp), causing a controlled periodical heat flow and thereby representing strongly damped thermal waves. These techniques make use of interference and reflection of thermal waves which allow enhancing depth resolution.

So far, only the temporal component of the light source was modified to achieve a defined vertical heat flow – In contrast, we propose a novel technique in which we are able to control both: time and space. This technique enables us to exploit the possibilities of coherent thermal wave shaping. We achieve that by combining a spatial light modulator (SLM) with a high power laser. This approach allows us to launch a set of individually controlled and fully coherent high energy thermal waves into the sample volume. That means, we intentionally use wave propagation throughout the sample's material in both - vertical and lateral direction.

As one possible application, we use a thermal waves' interference effect of two phase shifted wave patterns to detect the position of hidden defects. The wave patterns are positioned with a certain distance and a 180° phase shift to each other creating an amplitude depletion zone right in the middle of the two patterns. When a defect is brought unsymmetrically into the depletion zone, the lateral heat flow is disturbed. If the sample is now moved through the depletion zone, a defect can be easily characterized. Exciting periodically while controlling simultaneously phase and amplitude enables us to have a defined thermal wave propagation throughout the sample which means thermal waves can be controlled almost like acoustical or optical waves. This offers the opportunity to transfer known technologies from wave shaping techniques to thermography methods.

## Introduction

Detecting and characterizing subsurface and surface breaking defects is a major issue in quality assurance. Active thermography as a non-destructive evaluation method has shown its ability to detect small defects. However, thin subsurface defects perpendicular oriented to the surface are still difficult to locate. A rule of thumb states a defect is not detectable if the defect width to depth ratio is below one to two [1]. This rule is based on the assumption



that a homogenous illumination at the surface causes the heat flux to propagate perpendicular to the surface and parallel to the defect. There have been several approaches to locate perpendicular oriented defects by changing the direction of the heat flux [2-6]. However if the defect is closed to the surface methods, methods like the flying spot thermography need a defect free reference in order to enhance sensitivity.

In this paper we show a novel reference free approach to detect thin perpendicular oriented subsurface defects breaking the width to depth ratio of one. Our method is based on illuminating a sample with two oscillating line sources creating a fully coherent lateral heat flux. We use the superposition of thermal waves which was first introduced by Busse et al. [7]. Instead of using constructive superposition, as it was proposed, we use destructive superposition of thermal waves in order to achieve intrinsic reference free behavior. We attain that by using a complex illumination source, providing an array of individually addressable heat sources. In 2012, Holtmann first used a LCD projector as complex heating source [8]. As he used the internal light engine of a LCD projector he was limited in optical power. One approach to increase the optical power was proposed in the master thesis of Ravichandran [9]. He coupled an IR laser to a digital micromirror device (DMD) increasing the maximal applicable power. In a similar approach, we also couple a DMD to an IR laser. Furthermore, we control the timing between data acquisition and illumination in order to generate arbitrary controlled coherent thermal waves.

## **Experimental design**

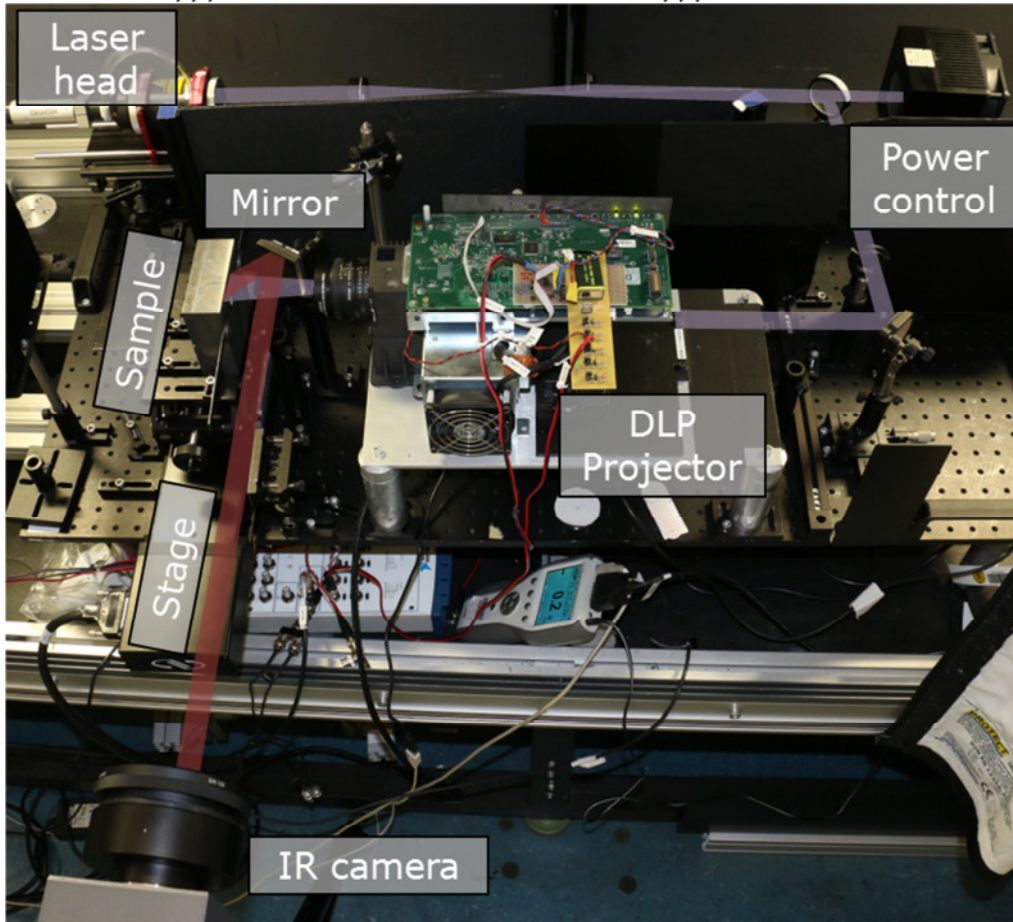
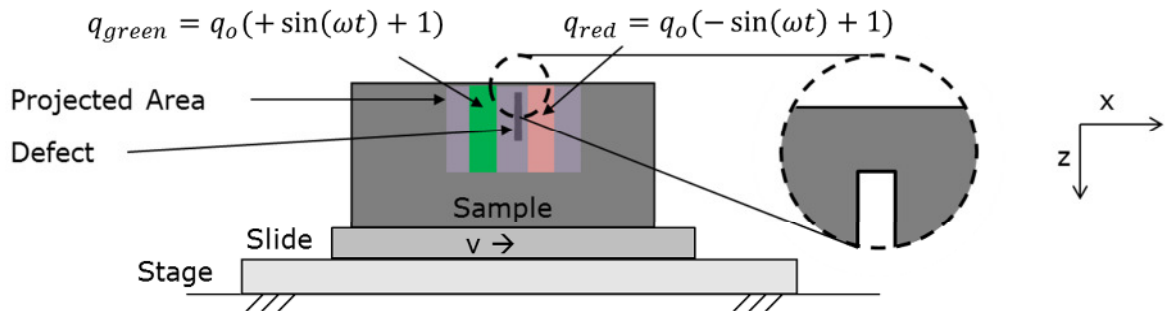
### *1.1 Measurement principle*

In order to detect perpendicular oriented subsurface defects, we illuminate a sample's surface with two oscillating linear patterns with the same intensity but of opposing phases (s. Fig. 1, top). We assume isotropic, homogenous material. Due to destructive interference of both thermal responses, the resulting alternating signal at the symmetry line between both patterns is zero. Therefore we name the symmetry line depletion line. If the material is inhomogenous i.e. due to a perpendicular crack, the resulting heat flow of either one of the sources is disturbed. Therefore the signal at the depletion line is unequal to zero which we use to detect the crack.

### *1.2 Experimental Setup*

Core of our method is a novel complex light source which allows us to control the heat flux throughout a sample's material. The light source consists of a DMD which is coupled to a fiber coupled diode laser (s. Fig. 1). The DMD is a mirror array of 1024 x 768 individually controllable mirrors which allows projecting any pattern to a sample. The sample itself is positioned on a stage which can be moved during measurement. The thermal response of the sample is projected in reflection configuration via a gold mirror to a high speed IR camera. Camera, stage and DMD are controlled by software ensuring time deterministic behavior between illumination and data acquisition.

Illuminated Pattern:



**Fig. 1.** (Top) Schematics of the sample positioned on a stage. The purple area shows the maximal area being illuminated by the projector. The green and the red line represent the oscillating patterns.

(bottom): Top view of the experimental setup showing a photo of a DMD coupled to a fiber coupled diode laser. In order to ensure that the DMD is not damaged, the input power is controlled. When the beam enters the DLP projector, the beam profile is converted from Gaussian to a top hat profile. The beam illuminates the DMD inside the projector whereas each mirror has two states on and off. The on state projects light to the sample whereas the off state projects to a beam dump

### 1.3 Sample Description

The sample is made of St37 steel with a size of 100 mm x 100 mm x 40 mm. An artificial crack of 20 mm x 10 mm x 0.53 mm has been fabricated by electrical discharge machining at 60 mm with a ligament of 0.95 mm (s. Fig. 1). This results in a width to depth ratio of 0.53 mm/0.95 mm = 0.56, i.e. smaller than one. Graphite spay has been used to coat the surface.

### 1.4 Illumination

The area being illuminated by the light source is 16 mm x 25 mm. The size of each illumination pattern is 5 mm x 16 mm with a distance of 5 mm to each other. We illuminate the sample with:

$$q_{green} = \frac{1.2 \text{ W}}{\text{cm}^2} (\sin(2\pi 0.125\text{Hz}) + 1) \quad (1)$$

and

$$q_{red} = \frac{1.2 \text{ W}}{\text{cm}^2} (-\sin(2\pi 0.125\text{Hz}) + 1) \quad (2)$$

That means the depletion line from the center line of the pattern is within the thermal diffusion length of  $\mu = 6.2$  mm.

### 1.5 Detection

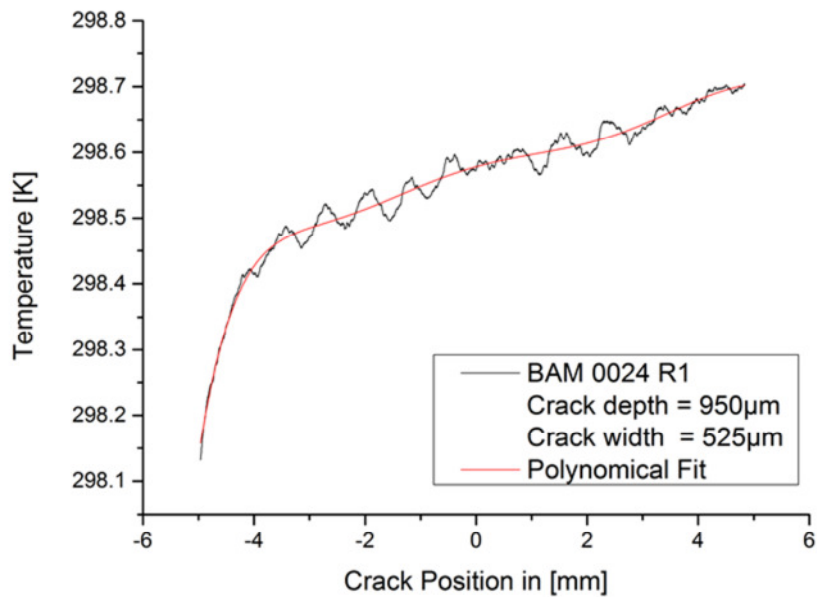
As detector type, we used a cooled InSb focal plane array which is sensitive in a wavelength range of 3  $\mu\text{m}$  to 5  $\mu\text{m}$ . The camera was calibrated for a temperature range of 10  $^{\circ}\text{C}$  to 60  $^{\circ}\text{C}$  at an integration time of 1140  $\mu\text{s}$ . The illuminated area was resolved with 320 Pixel x 256 Pixel at an acquisition rate of 50 Hz. The noise-equivalent temperature difference is below 25 mK.

### 1.6 Testing procedure

The projected patterns are calculated in advance. Coordinate systems of projector, linear stage and camera need to be correlated. The defect position is set to zero in the linear stage coordinate system. During the measurement, the sample is moved from -5 mm to 5 mm at a velocity of  $v = 0.1$  mm/s while controlling simultaneously data acquisition and pattern projections.

## 2. Data analysis

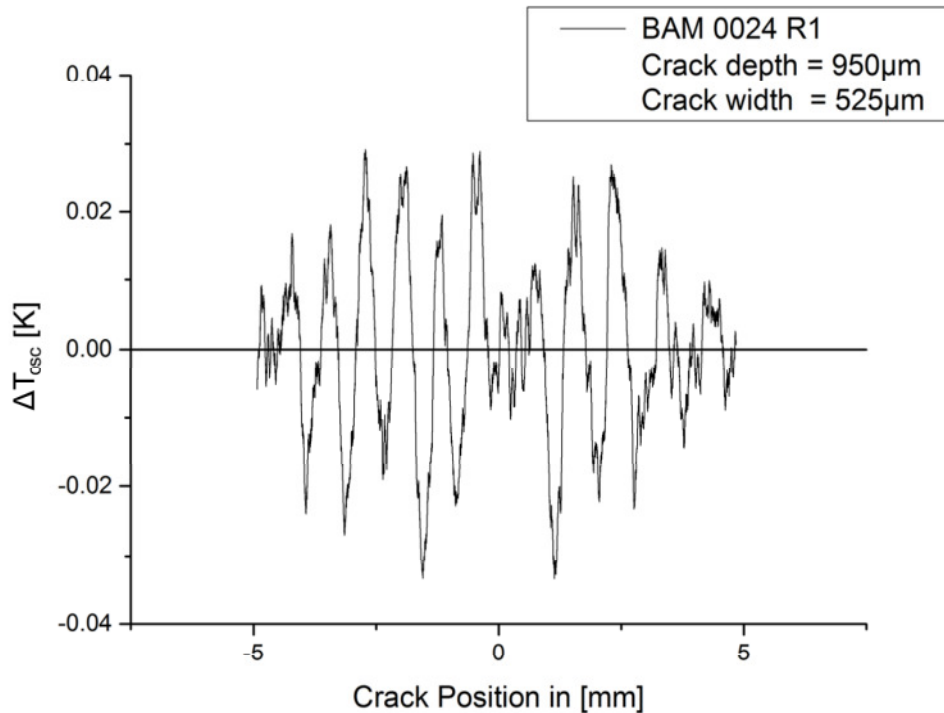
The measured temperature dataset represents the temperature at the surface over time  $T_{cam}(x_c, y_c, t)$ . Because the data is projected via a mirror, the dataset  $T_{cam}(x_c, y_c, t)$  is distorted and therefore transformed to the projector coordinate system  $T_{proj}(x_p, y_p, t)$ . The data is extracted at the depletion line  $T_{depl}(x_{depl}, y_p, t)$ . In order to reduce noise  $y_p$  is chosen as averaged range from  $y_{pstart}$  to  $y_{pend}$ . Furthermore, the data set is also averaged along the time axis. At last, the time  $t$  is multiplied with the stage's velocity computing the position. The resulting graph is shown in Fig. 2. It shows the temperature at the depletion line related to the crack position. Removing the general temperature rise, we fit a polynomial of 6<sup>th</sup> degree to the graph and subtract it. The result is shown in Fig. 3.



**Fig. 2.** The black line shows the temperature at the surface of depletion line. The crack is located between 0 mm and 0.5 mm. The red graph shows a fit which is used to remove the general temperature rise.

### 3. Results and discussion

In order to demonstrate the principle of interference based crack detection we scanned two coherent oscillating patterns over a homogenous isotropic material with an inserted artificial crack in a depth of 0.95 mm. The illumination intensity and frequency of the oscillation was equal but they had a phase shift of  $\pi$  to each other. As described beforehand at the symmetry line between both patterns the alternating part of thermal response is depleted. When we scan over a vertical hidden crack, the lateral heat flux is disturbed resulting in an alternating part of the thermal response. Only if the crack is in the middle of both patterns, symmetry is fulfilled, also resulting in depletion. This behavior is exactly shown in Fig. 3. It shows the alternating part of the thermal response at the depletion line. The crack is moved with a constant velocity through the oscillating patterns starting from -5 mm to 5 mm. Starting from the left, the crack is right beneath the green pattern (s. Fig. 1) which disturbs the depletion only little. When moving the crack to the middle, the amplitude rises which means the crack forms a big barrier to the green heat flux pattern (s. Fig. 1). Moving the crack to the middle, the amplitude falls down to a minimum. As predicted, symmetry is now fulfilled. Amplitude starts to rise again when moving the crack to the right. That means the crack now impedes the heat flow of the red pattern. Further to the right, the amplitude decreases again. The graph is symmetrical whereby the minimum of the amplitude correlates with the crack position at 0 mm.



**Fig. 3:** The black graph shows the oscillating temperature part at the surface of the depletion line. As the crack has a width of 0.525 mm it is located from 0 mm to 0.5 mm

#### 4. Conclusion

The presented technique uses the destructive interference effect to locate an artificial defect with a width to depth ratio of 0.55. The method makes use of launching fully coherent thermal waves which is possible by using a laser coupled DMD.

#### References

- [1] X.P. Maldague, Introduction to NDT by active infrared thermography, *Materials Evaluation*, 60 (2002) 1060-1073.
- [2] S. Lugin, Detection of hidden defects by lateral thermal flows, *NDT & E International*, 56 (2013) 48-55.
- [3] T. Li, D.P. Almond, D.A.S. Rees, Crack imaging by scanning laser-line thermography and laser-spot thermography, *Meas. Sci. Technol.*, 22 (2011).
- [4] J. Schlichting, C. Maierhofer, M. Kreuzbruck, Crack sizing by laser excited thermography, *NDT & E International*, 45 (2012) 133-140.
- [5] J. Schlichting, *Integrale Verfahren der aktiven Infrarotthermografie*, 2012.
- [6] Y.Q. Wang, P.K. Kuo, L.D. Favro, R.L. Thomas, A Novel "Flying-Spot" Infrared Camera for Imaging Very Fast Thermal-Wave Phenomena, in: J.C. Murphy, J.W.M. Spicer, L.C. Aamodt, B.S.H. Royce (Eds.) *Photoacoustic and Photothermal Phenomena II: Proceedings of the 6th International Topical Meeting*, Baltimore, Maryland, July 31–August 3, 1989, Springer Berlin Heidelberg, Berlin, Heidelberg, 1990, pp. 24-26.
- [7] G. Busse, K.F. Renk, Stereoscopic depth analysis by thermal wave transmission for nondestructive evaluation, *Applied Physics Letters*, 42 (1983) 366-368.
- [8] N. Holtmann, K. Artzt, A. Gleiter, H.P. Strunk, G. Busse, Iterative improvement of Lockin-thermography results by temporal and spatial adaption of optical excitation, *Quantitative InfraRed Thermography Journal*, 9 (2012) 167-176.
- [9] A. Ravichandran, Spatial and temporal modulation of heat source using light modulator for advanced thermography, (2015).