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Using spatial and temporal shaping of laser-induced diffuse thermal wave fields in thermography

M. Ziegler[1], S. Ahmadi[1], P. Hirsch[1], J. Lecompagnon, C. Hassenstein[1], E. Thiel[1], N. W. Pech-May[1]
[1]Bundesanstalt für Materialforschung und -prüfung, 12200 Berlin, Germany,
samim.ahmadi@bam.de

Summary:
The diffuse nature of thermal waves is a fundamental limitation in thermographic nondestructive testing. In our studies we investigated different approaches by shaping the thermal wave fields which result from heating. We have used high-power laser sources to heat metallic samples. Using these spatial and temporal shaping techniques leads to a higher detection sensitivity in our measurements with the infrared camera. In this contribution we show our implementation of shaping laser-induced diffuse thermal wave fields and the effect on the defect reconstruction quality.

Keywords: thermal wave, diffusion, high-power laser, thermography, spatiotemporal shaping

Introduction

In infrared thermography, the interaction of the heat flow with the internal geometry or inhomogeneities in a sample and their effect on the transient temperature distribution is used, e.g. to detect defects non-destructively. An equivalent way of describing this is the propagation of thermal waves inside the sample. Although thermography is suitable for a wide range of inhomogeneities and materials, the fundamental limitation is the diffuse nature of thermal waves and the need to measure their effect radiometrically at the sample surface only [1]. The crucial difference between diffuse thermal waves and propagating waves, as they occur e.g. in ultrasound, is the rapid degradation of spatial resolution with increasing defect depth. A promising approach to improve the spatial resolution and thus the detection sensitivity and reconstruction quality of the thermographic technique lies in the shaping of these diffuse thermal wave fields [2, 3]. For example, narrow crack-like defects below the surface can be detected with high sensitivity by superimposing several interfering thermal wave fields, closely adjacent defects can be separated by multiple measurements with varying heating structures and defects at different depths can be distinguished by an optimized temporal shaping of the thermal excitation function. We present the latest results of this technology obtained with lasers, i.e. spatially and temporally structureable heating sources and modern numerical methods.

Techniques for shaping thermal wave fields

The spatiotemporal shaping of thermal wave fields can be realized by using different techniques. Thus, we investigated the effect of spatial shaping by using different illumination techniques. These illumination techniques are strongly depending on the material since the absorption spectra differ a lot.

We decided to compare homogeneous illumination (flash over the whole surface of the specimen) with structured illumination (laser lines with a certain width).

To realize structured illumination, we first have used a diode laser in combination with a digital mirror device (DMD) which enabled us to create diverse illumination pattern [4].

Another technique to ensure structured illumination was to use a vertical cavity surface emitting laser (VCSEL) array. The VCSEL array consists of 12 laser lines, the image size could be controlled by using lenses. Hence, the user was able to control the laser line width for our studies.

Instead of using the VCSEL array, we could use a fiber-coupled high-power laser, too. For this laser we have used different optics to create rectangular laser illumination or laser lines with different sizes.

Temporal shaping has also been investigated within our studies. Therefore, we set up a real-time FPGA based control system which was controlled via LabView.

We applied different laser pulse lengths in our experimental studies. In addition, we implemented lock-in thermography where we make use of an amplitude modulation of our laser sources.

Apart from these state-of-the-art techniques we also applied thermal wave interference methods to investigate the improvement of defect detection. In this technique we made use of destructive interference of two anti-phased amplitude modulated heat source [3].

Further, we investigated the possibility of using pulse compression with our laser sources. Similar to radar applications [5], we try to extract our original pulse compressed signal in our noisy measured data by using the cross-correlation with our original sequence. Therefore, we use different coding techniques by making use of e.g. Barker-codes [6].

Our newest studies refer also to photothermal super resolution inspection techniques [7,8] where we scan the whole surface of a specimen using different illumination techniques which all rely on the same principle: performing a lot of measurements by illuminating different positions using position shifts which are smaller than the laser line width. Consequently, we create a measurement set where some of the measurements are overlapping.

Results using thermal wave field shaping

Our studies have shown that the use of spatial and temporal shaping has a high potential since we could beat the conventional thermographic resolution limits given by simple homogeneous illuminations using flash lamps.

Laser arrays such as our used VCSEL array provide a maximum output power of 2.4 kW which is much higher than the output power of the combination of a laser diode and a DMD since the DMD is not designed for high-power applications.

We discovered that our destructive interference method enables to better resolve narrow subsurface defects than flash lamps.

Furthermore, it turned out that Barker-Codes could be very helpful to increase the quality of the measured signal which is of high interest if the signal-to-noise ratio is very small.

Finally, our studies have shown that we can also make use of super resolution scanning strategies for better separating closely spaced defects. We could enhance the spatial resolution artificially by deconvolving the measured data with the thermal point spread function.

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