CHARACTERIZING CRACKS WITH ACTIVE THERMOGRAPHY

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1. Introduction

The detection of open surface cracks is an important task to prevent structural failure. Especially with regard to the widespread use of low ductility, high performance steel in lightweight construction, this is a subject of increasing interest.

There are several conventional NDT methods for crack detection. For example dye penetrant and magnetic particle inspection have been used for decades with great success. But these methods are generally unsuited for crack depth resolution. In addition direct access to the surface under investigation is required and expendable materials are used.

Usually the geometrical parameters of cracks are accessible with x-ray computer tomography (CT). In many cases ultrasound (UT) and – with certain restrictions - eddy current testing (ET) can provide deeper insight into the size and orientation of the material defect.

While with CT high-resolution 3D images of high geometrical accuracy are obtainable, this method is rather time consuming and expensive when pushing it to the limits.

UT and ET, the other reference NDT methods have of course proven to cover a great variety of testing problems and are very cost-effective because of their widespread use. But both methods require close access to the surface and are limited in testing speed if scanning is required for better spatial resolution. Furthermore ET is limited to electrical conductive materials and when testing anisotropic materials, it is problematic to gain unambiguous results by UT.

Thermography is a fast areal NDT method. In conventional setups, a relatively homogenous heat flow is applied perpendicular to the surface by flash or halogen lamps [1], then the resulting temperature distribution at the surface is recorded with an infrared camera, allowing to estimate the heat flow in the object. In doing so it is possible to resolve a broad variety of defects, such as voids, pores, or delaminations. But due to the perpendicular heat flux it is only possible to resolve changes

in the thermal properties in this direction. Cracks oriented perfectly perpendicular have no effect on the perpendicular heat flow, and thus cannot be detected in most cases.

To tackle this problem, common thermographic methods for crack-detection recently also applied defect selective ultrasonic [2] and inductive [3] excitation. Although at least for induction thermography quantitative relations are known [4], these methods are up to now mostly used for qualitative analysis only. Another method, which currently experiences intense research activities, is the so called "flying spot laser thermography". This approach uses a laser, which is scanned over the surface. Changes in the heat conductivity lead to changes in the thermal footprint, which is then used for crack-detection. A good overview about crack-detection with laser thermography can be found elsewhere [5]. But with all these methods mentioned here, it is not possible to accomplish a fast, contact-free and reliable crack characterization of all relevant parameters.

In this work an advanced technique to characterize the crack depth by active thermography is presented. A laser is used for heating at a fixed position in proximity to the crack. The disturbance of the lateral heat flow caused by the crack leads to an unsymmetrical thermal footprint of the laser. A quantitative analysis of this effect is used to determine the crack depth.

It is a major positive aspect of this method, that it is based on well known physical effects, which particularly do not include any interference or chaotic behavior. So simulation could be robust and reliable. This is proven by comparing experimental results with FEM analysis, which are subject of an additional article in these proceedings.

2. Experimental Setup

The experimental work presented here was conducted at the "thermoshock facility" (see Fig. 1). The spot of a 1000 W cw Nd:YAG laser is projected by scanner optics to the sample surface. The thermal response is recorded by a Raytheon InSb IR camera with a spatial resolution of 256 x 256 px. The sample itself is placed in a vacuum chamber, so different environmental conditions can be applied.

The test specimen used for calibration was a 10 x 10 x 4 cm³ block made of st37 construction steel with four spark eroded cracks (see Fig. 2). It was graphite coated for higher emissivity. The measured temperature was calibrated by applying a thermocouple in the hole on the backside.
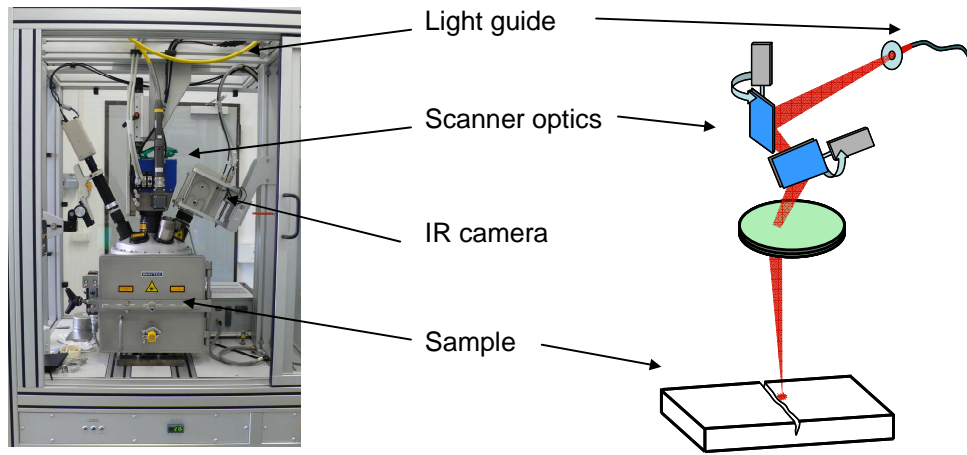
Figure 1. Photo (left) and sketch (right) of the experimental setup. The Laser is not shown at the left image. The yellow line is the fiber-optic light guide connecting laser and scanner optics. Specifications: Laser Nd:YAG, 1000 W cw, camera InSb max 256x256 px, 128x128 px @ 500 Hz.

3. Measurements

To perform the crack sizing, a fixed laser spot position was used for heating and the asymmetries in the laser's thermal footprints caused by the thermal resistance of the cracks were analyzed. Using this particular experimental setup, best result were obtained with an excitation for 2 s at 25 W laser power, so assuming an emissivity of 0.8 a heat energy of 40 J is deposited in the material. The spot was positioned at distances of 1, 1.5, 2, 3, and 5 mm at both sides of each crack as seen in Fig. 3.

For data analysis the following procedure was used (see Fig. 4). Two reference areas are defined (A1, A2) in equal distance e to the laser spot. For different spot positions the distance c between A1 and the crack is fixed. The difference between the spatial mean intensity respectively temperature values in both reference areas is taken. The mean value in time of this expression is defined as crack depth value cdv:

$$cdv := \frac{1}{t}\int_{t1}^{t2} d\tilde{t}\,\Delta T(\tilde{t})\qquad(1)$$
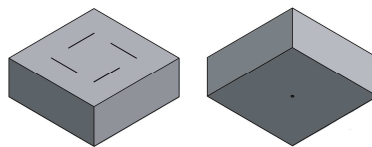

Figure 2. Test specimen used for calibration. 10x10x4 cm³, 4 spark-eroded cracks on the top side: 1,2,3, and 4 mm deep, ~0.2 mm wide, a hole for contact thermometer at the bottom side.
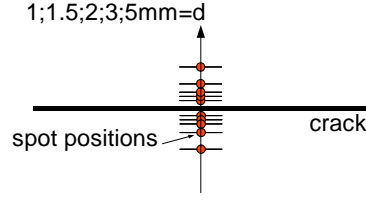
Figure 3. Laser spot positions for different crack-to-spot separations.

For this setup $t1=1$ s and $t2=1.6$ s were beneficial. Using the described procedure a single number of high signal to noise ratio is obtained as a figure of merit for the crack depth.

In Fig. 5 we depict the cdv as function of different crack-to-spot separations for several crack depths to determine optimum spot and reference positions. We observe that:

- A high signal-to-noise ratio is obtained
- The distance between spot and crack should be minimized
- The cdv increases with increasing crack depth
- The crack depth can be distinguished in mm-steps
- The detection sensitivity for different crack depths decreases with crack depth

Although the spot should be close to the crack, we want to mention, that illumination of the crack itself should be avoided. Otherwise this would lead to undefined application of thermal energy resulting in lower and not reproducible cdv. Having this in mind, we have to account for the power distribution of the laser spot itself. A widely used model is a Gaussian distribution, which is unfortunately not limited in space. In our case the laser spot has a diameter (FWHM) of about 1 mm. It turned out, that a distance of 1 mm between the spot's centre and the crack is sufficient to significantly direct crack-heating effects.
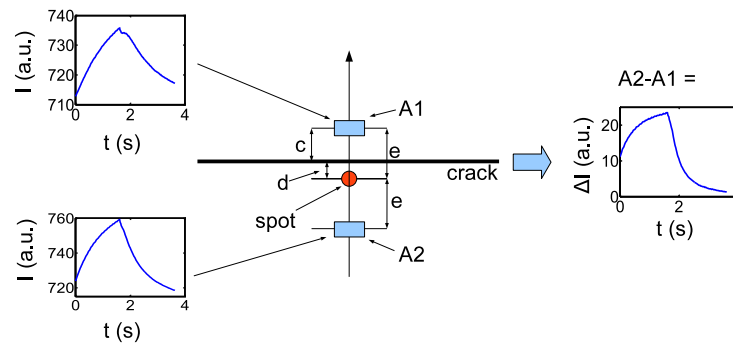

Figure 4. Data analysis procedure: The difference between the measured transient intensities in two reference areas (A1 & A2) equidistant to the laser-spot can be used for determining crack-depth. The plots show intensities of thermal radiation in digital levels vs. time in seconds.
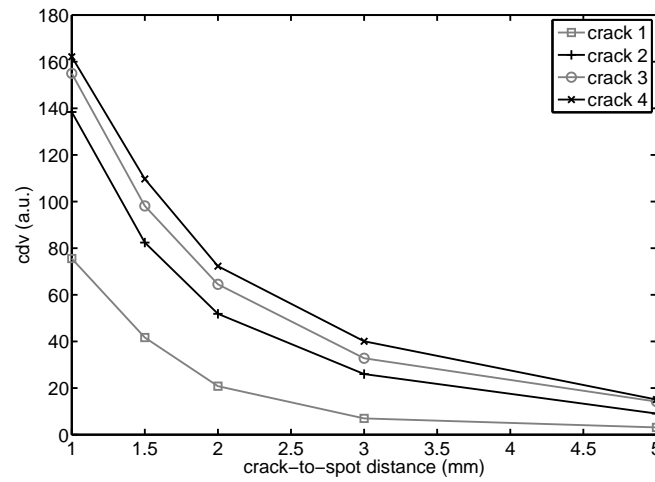
Figure 5. cvd as function of crack-to-spot distance d for different crack depths (crackX: depth X mm)

3. Comparison with numerical results

Numerical studies with the same geometrical parameters performed with a commercial FEM package [6] are presented in an other contribution to these proceedings [7].

The data reveals a quite good overall correlation between simulated (2D or 3D?) and experimental results (Fig. 6). The deviations can be explained by different possible effects. The high thermal inertia of the test specimen led to difficulties while performing the temperature calibration. Uncertainties in the exact distribution of the laser spot should also be taken into consideration.
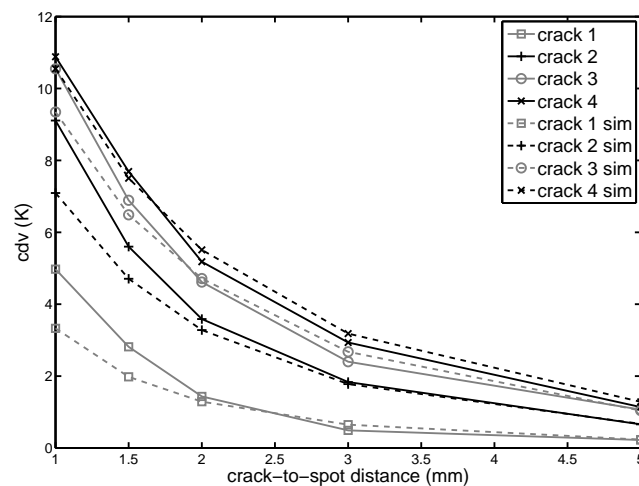

Figure 6. Comparison of experimental and numerical results: cvd as function of crack-to-spot distance d for different crack depths.

By performing parameter variations the influence on different geometrical uncertainties was studied (Fig. 7). It should be emphasized, that a proper geometrical calibration is very important. Small changes in symmetry of the positions of the reference areas relating to the spot position led to significant errors. A shift of 10% already makes the individual crack depths nearly undistinguishable. A realistic uncertainty in the exact crack position is far less critical. With an error of 0.1 mm in the position of the crack, its depth can still be characterized with a mm resolution.

4. Summary and Outlook

The use of laser excited thermography not only enables us to detect surface defects, but to characterize the crack depth as well. Because of its differential character - only the differences between two reference areas are taken to account - this method appears to be robust to environmental influences, like e.g. changing background illumination and inhomogeneous emissivity. Because no direct is required, this approach seems to be well suited for automation.

We would like to point out, that these findings just demonstrate the feasibility of crack-depth characterization for relatively long notches. The influence of the crack length and the amount of heat flow passing at the lateral edges of the defect still has to be investigated experimentally. In addition, the influence of the crack gap is still an intensely discussed issue. Further simulations and experiments are required to distinguish the effects of depth and gap more precisely.
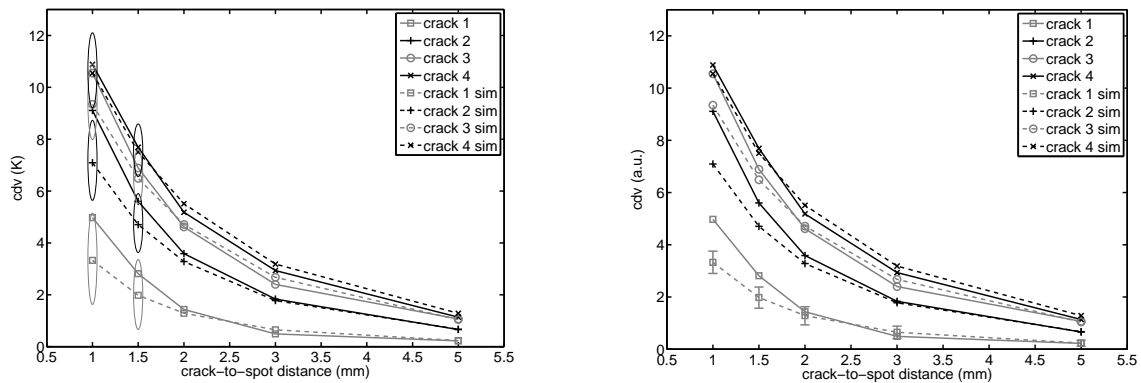

Figure 7. Influences of geometrical uncertainties: For the left plot the position of the reference areas was asymmetrically shifted by 10%. In the right plot the influence of 0.1mm deviations in the crack-positions is shown.

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