DEFECT SIZING BY LOCAL EXCITATION THERMOGRAPHY

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Abstract

In this article, we present a measurement procedure to gain information about depth and angle of open surface cracks. The method is based on a local excitation with, e.g., a laser. The resulting surface temperature is recorded with an infrared camera. Based on this data, crack-caused anisotropies in the lateral heat flow can be detected and exploited to characterise the cracks.

The experimental set-up is based on a Nd:YAG laser. The beam is focused on the test sample by using an optical scanner to generate the required lateral heat flow. The time resolved temperature distribution is recorded with a high-speed infrared camera (InSb FPA, 3 to 5 µm) providing a frame rate of up to 500 Hz.

Up to now, only qualitative information was gained from measurements of this type. Whereas the local transient behaviour of temperature distribution provides also quantitative information of the crack parameters. The general concept of the method presented herein has already been published [1], but the mentioned publication is focused on the crack depth only.

In this paper, we can show that it is possible to simultaneously resolve the angle and depth and, in particular, the depth of non-perpendicular cracks.

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 great 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 sufficient spatial resolution. Furthermore ET is limited to electrically conductive materials and when testing anisotropic materials, it is problematic to gain unambiguous results by UT.

Thermography is a fast imaging NDT method. In conventional setups a relatively homogeneous heat flow is applied perpendicular to the surface by flash or halogen lamps [1]. The resulting temperature distribution at the surface is recorded with an infrared camera, allowing estimating the heat flow into the object. In doing so it is possible to resolve a broad variety of defects, such as voids, pores, or delaminations. On the other hand due to the perpendicular heat flux it is only possible to resolve changes in the thermal properties normal to the surface. Cracks oriented perpendicular to the surface have no effect on the heat flow, and thus cannot be detected.

To tackle this problem, common thermographic methods for crack-detection recently also include the defect selective ultrasonic [2] and inductive [3] excitation. Although at least for induction thermography quantitative relations are known [4], up to now these methods are 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 consequently lead to changes in the thermal footprint, which is used for crack-detection. A single infrared (IR) detector element is sufficient to detect cracks [5], but

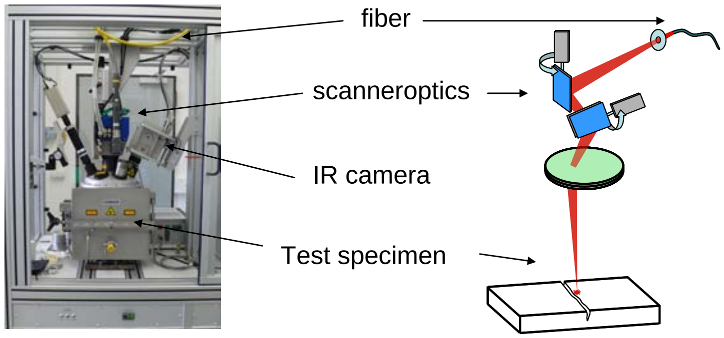

Fig. 1: *Photo (left) and sketch (right) of the experimental setup. The Laser is not shown at the left image. The yellow line is the fiber-optic light guide connecting laser and scanner optics. Specifications: Laser Nd:YAG, 1000 W cw, camera InSb max 256x256 px, 128x128 px @ 500 Hz.*

nowadays an IR camera is state of the art. A good overview about crack detection with laser thermography can be found elsewhere [6]. But with all these methods mentioned here, it is not possible to accomplish a fast, contact-free and reliable crack characterization.

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 asymmetric thermal footprint of the laser. A quantitative analysis of this effect is used to determine the crack depth.

2. Procedure for the determination of crack depths

A procedure for determination of crack depth has been presented in Ref. 8. The procedure has been validated with experimental data and FEM simulations. A short summary of the results will be given in the following part.

2.1. Measurements

The experimental work presented therein was conducted with the "thermoshock facility" (see Fig. 1). The spot of a 1000 W continuous wave Nd:YAG laser is projected by 2D scanner optics to the sample surface resulting in a spot diameter of 1 mm. The thermal response is recorded by a Raytheon InSb IR camera with a spatial resolution of 256 x 256 pixels. For calibrating the analysis procedure, test specimen sized 10 x 10 x 4 cm^3 made of st37 construction steel with four spark eroded cracks (see Fig. 2) were used. To perform the crack sizing, a fixed laser spot position was used for heating and the asymmetries in the laser's thermal footprint caused by the thermal resistance of the cracks were analyzed. Using this particular experimental setup, best results were obtained with an excitation for 2 s at 25 W laser power. Assuming an emissivity of 0.8, a heat energy of 40 J is deposited into the material.

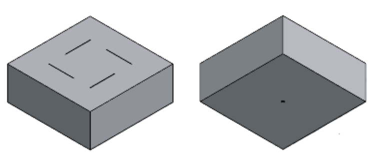

Fig. 2: *Test specimen used for calibration. 10x10x4 cm^3, 4 spark-eroded cracks*

2.2 Data Analysis and Simulations

For data analysis the following procedure was used (see Fig. 3). 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 detected spatial mean intensity or temperature values Δ*T*, respectively, in both reference areas is taken. The mean value in terms of this expression is defined as crack depth value *cdv*:

$$cdv := \frac{1}{t_n - t_1} \sum_i t \cdot \Delta T(t_i) \quad (1)$$

For this setup *t1*=1 s and *t2*=1.6 s were beneficial. Using the described procedure a single number of high signals to noise ratio is obtained as a figure of merit for the crack depth. In Ref. 8 an in-depth discussion on FEM simulation on the same geometry is given. For the simulation presented therein, a commercial finite element solver was used [9]. A good consistency between simulations and experimental data was obtained.

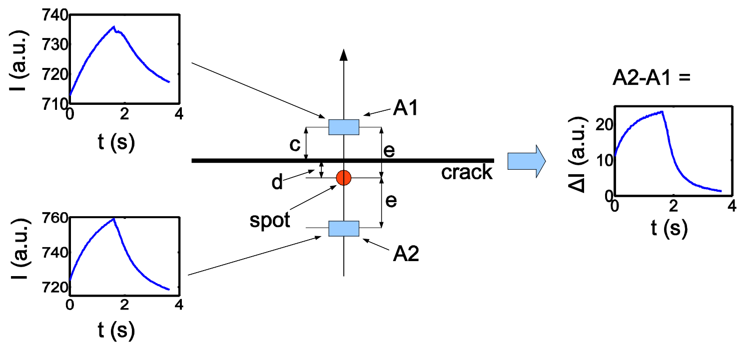

Fig. 3: *Data analysis procedure: The difference between the measured transient intensities in two reference areas (A1 & A2) equidistant to the laser-spot can be used for determining crack-depth. The plots show intensities of thermal radiation in digital levels vs. time in seconds.*

2.3. Results and Conclusions

In Fig. 4 we depict the *cdv* as function of different crack-to-spot separations for several crack depths to determine optimum spot and reference positions. In particular, we observed the following:

- A high signal-to-noise ratio is obtained.
- The distance between spot and crack should be minimized.
- The crack depth can be distinguished in mm steps.
- The relative error increases with crack depth.

Although the spot should be close to the crack, it has to be mentioned that illumination of the crack itself should be avoided. Otherwise this would lead to undefined application of thermal energy resulting in non reproducible results.

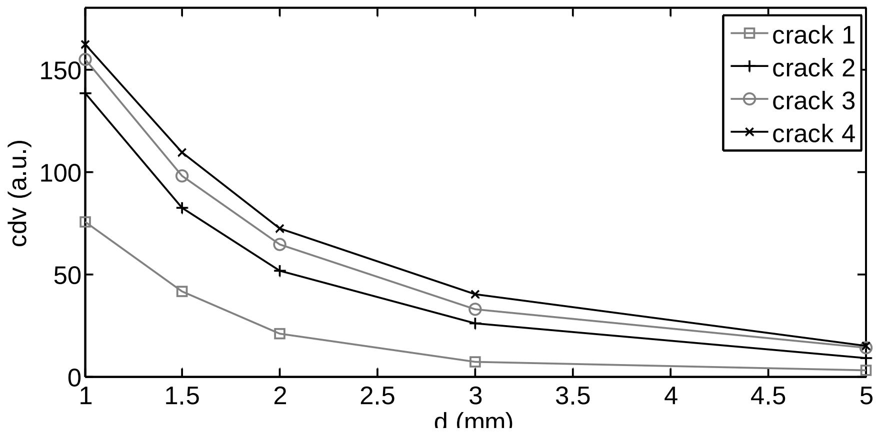

Fig. 4: *Crack depth value cdv for crack depth of 1 to 4 mm, derived by using the analysis procedure depicted in Fig. 3, plotted versus crack to spot distance d.*

3. Determination of crack angles

A major positive aspect of thermography is, that it is based on well known physical effects, which particularly do not include any interference or chaotic behavior. Therefore simulation should be robust and reliable. This was proven by comparing experimental results with FEM analysis [8].

In this part a technique for determining geometrical parameters is developed by analyzing data from FEM simulations. The advantage of using simulated data is based on the low numerical noise level which is several orders of magnitude below the electronic noise of a thermo sensing device, thus nearly arbitrary small parameter variations are possible. In doing so, the influence of noise on the detection limit can be quantified.

To compare the results of measurements or simulations recorded with different parameters, an adequate criterion is needed. The optimal solution would be a single number.

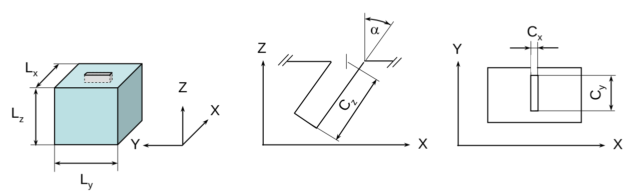

Fig. 5: *Parameterization of cuboid shaped cracks. For the crack itself the 3 linear dimensions C_i and the angle α are sufficient.*

3.1. FEM Simulations

The geometries were studied numerically using a commercial finite element analysis and solver software package [9]. The width of the crack was set to C_x = 0.2 mm, the length C_y = 30 mm (denomination see Fig. 5). A mesh with about 40,000 elements resulted in a sufficient accuracy. The element size was not chosen uniformly, but finer at the crack and the laser beam positions, because the highest heat flow gradients are expected at these positions. For further data analysis the heat distribution at the surface was generated with a resolution of 64 x 64 pixels symmetrically positioned around the crack. The pixel size is 0.67 mm. The mesh was generated in a way that each pixel is represented by a mesh node. Again, the laser excitation is modelled with 25 W for 2 s and a spot diameter of 1 mm. For the parameter study one simulation took about 20 min on an 8 core workstation.

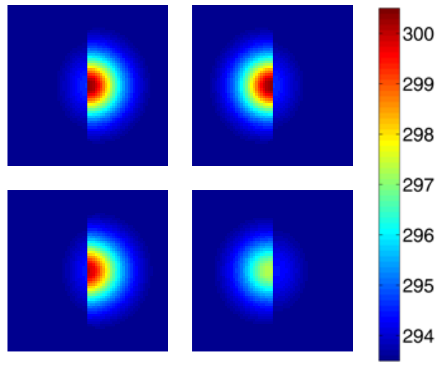

Fig. 6: *Results of two simulation runs: surface temperature in K for t=3 s. Upper pictures for α=0°, lower for α=30°. The asymmetrical heat flow for an askew crack is clearly visible in the lower pictures. Left: Laser spot at the right hand side. Right: Laser spot at the left hand side.*

3.2. Data analysis procedure

A simultaneous determination of crack depth C_z and angle α is possible with an adapted version of the crack depth value *cdv*. For such an adapted version, two experiments with laser excitation on different sides of the crack have to be evaluated. The other parameters, in particular the position of the reference areas A1 and A2 relative to the laser spot position, should be unchanged. The crack depth values achieved by using the procedure presented in the previous part should be *cdv1* and *cdv2* (Fig. 7). The mean of these values *cdv=(cdv1+cdv2)/2* should primarily depend on the crack depth (C_z). The difference is called "crack angle value" *cav=cdv1-cdv2*, which represents a quit good criterion for the angle α. Because both values represent a spatial and temporal average they are robust to experimental noise.

Fig. 8 reveals that *cdv* (left panel) is primarily sensitive to the crack depth C_z. The *cav* (right panel) equals zero for α=0°, like it is expected. It is rising with the skewness and depth of the crack under investigation. Calculating these two values enables us to uniquely determine angle and depth as evidenced in Fig. 9, where isolines for *cav* and *cdv* are plotted. Each *cdv*-line has only one point in common with each *cav*-line, hence it follows that an unambiguous assignment is possible.

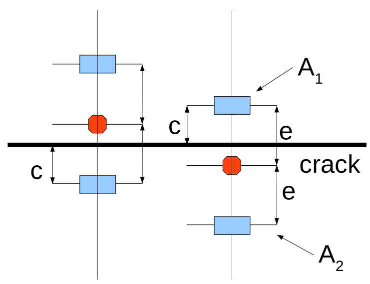

Fig. 7: *cdv is calculated for laser spot positions on both sides of the crack.*

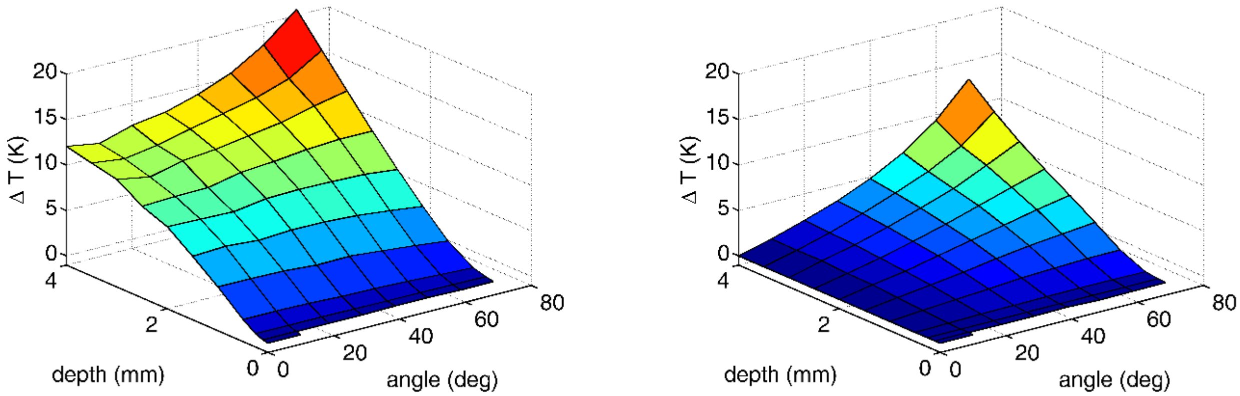

Fig. 8: *Left:* cdv=(cdv1+cdv2)/2 *is primarily sensitive to the crack depth* C_z *.Right:* cav=(cdv1-cdv2) *is primarily sensitive to the crack angle α.*

3.3. Resolution Limits

Nowadays infrared cameras achieve a thermal resolution of up to 20 mK. The spatial and temporal averaging included in the method presented in this article results in nearly completely negligible statistical uncertainties. Assuming that the reference areas consist of 50 pixels each and 100 frames are taken into account, the relative error is smaller by a factor of 70 compared to the value of a single pixel at a single time. Thus rather systematic errors such as an improper calibration or an inhomogeneous emissivity at the sample surface will be the crucial factor.

In Fig. 10 *cav* and *cdv* are plotted for small crack depths and big angles. Even for angles as high as 60° or 70° a temperature resolution of only 200 mK is sufficient for detecting cracks with depth of only 0.5 mm. With these preconditions for a crack depth of only 1 mm an angle resolution of 10°-steps is still possible. But one should keep in mind when going to these small aspect values, that the used geometry with a crack width of 0.2 mm is becoming unsuitable. A 0.5 mm deep crack is only 2.5 time deeper than broad.

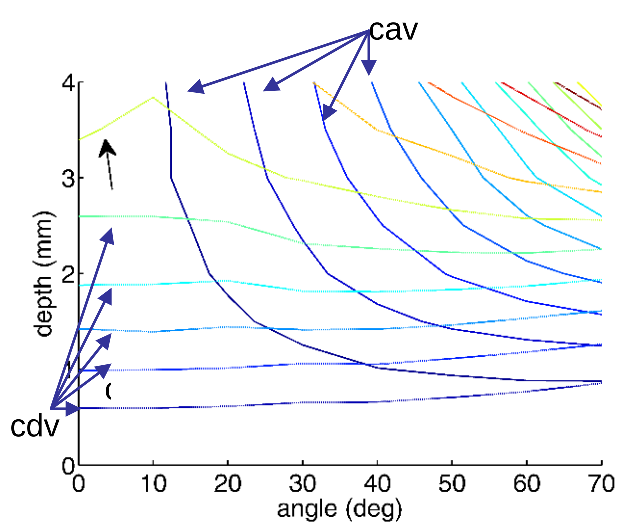

Fig. 9: *Isolines (same value on the line) for cav and cdv. The black arrow indicates an outlier, which could be a consequence of the coarse parameter variation.*

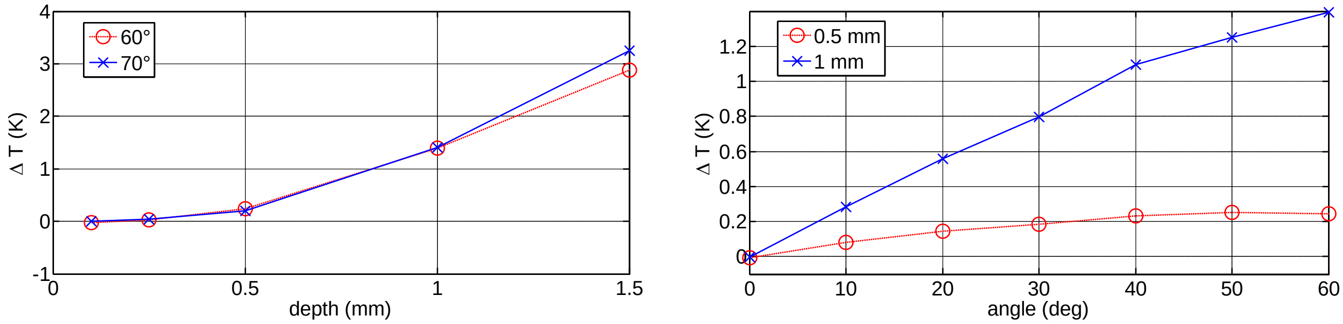

Fig. 10: *Left: cdv for small depth. Even for angles as high as 60° or 70° a temperature resolution of only 200 mK is sufficient. for detecting cracks with depth of only 0.5 mm. Right: cav for big angles. With the given thermal resolution for a crack depth of only 1 mm an angle resolution of 10°-steps is still possible*

4. Conclusion and Outlook

The use of laser excited thermography not only enables us to detect surface defects, but to characterize the crack depth and angle, as well. Because of its differential character - only the differences between two reference areas are taken into account - the method presented herein appears to be robust to environmental influences, like e.g. changing background illumination and inhomogeneous emissivity. Because no direct or at least near contact 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. In addition, the influence of the crack gap is an intensely discussed issue. Further simulations and experiments are required to distinguish the effects of depth and gap more precisely.

As a precondition to use this method the crack position has to be known precisely. We would propose to use an automated combined measurement procedure (see Fig. 11), using flying spot thermography [5,6] for crack detection and in a second step the method presented herein for a more precise investigation. The testing algorithm could be implemented in a way that one measurement with a fixed spot position could be sufficient to reject big flaws, which would increase the testing speed. There are two main advantages of this approach: First, both techniques utilize the same equipment. And, secondly, false-positive results from the flying spot crack detection are uncritical. Consequently a low detection threshold and a high scanning speed can be chosen. This approach could be easily integrated to existing flying spot setups, because no additional equipment is needed. This would result in increased detection reliability.

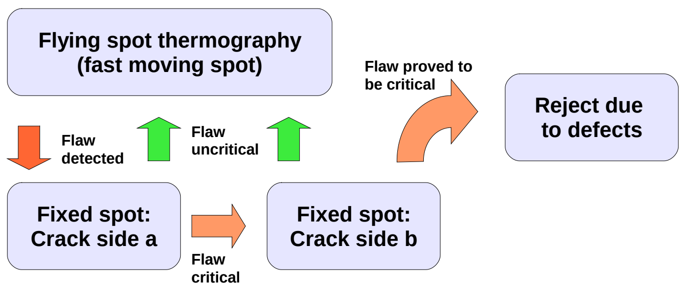

Fig. 11: *Possible procedure for crack detection and characterization.*

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