Flying Laser Spot Thermography for the Fast Detection of Surface Breaking Cracks

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Abstract
We report on recent developments in the detection of surface breaking cracks using flying laser spot thermography. Application of an infrared camera for mapping the thermal radiation after excitation with a diode laser equipped with an optical scanner allows us to examine a surface containing cracks in an entirely non-destructive, contactless and fast way, without even moving the camera. We developed an efficient and robust algorithm that can be applied directly to the recorded thermal sequences, and that derives a single image containing all crack signatures. For this crack detection technique, no specific synchronisation between laser and camera is required. Hence, our approach is suitable for an upgrade of existing thermographic systems. The feasibility of the proposed procedure is proven by testing an artificial test sample and a piece of rail that comprises roll contact fatigue cracks and by comparing the results with magnetic particle testing.

Keywords: Thermography, cracks, laser, flying spot.

1. Introduction

The detection of surface breaking cracks in safety relevant structures is an important NDT task. There are many techniques tackling this problem, like for instance eddy current, ultrasound, dye penetration, and magnetic particle testing. Flying laser spot thermography is another promising technique for the detection of such surface flaws. Local heating of the sample surface is realized by a laser, which is scanned over the surface. Local changes in the heat conductivity introduced by cracks then lead to changes in the laser’s thermal footprint. Due to the scanning character in principle a single IR sensor is sufficient, if it is scanned too at a fixed distance from the laser. This method is known as the "flying spot camera" and was suggested by Kubiak [1]. There is ongoing research on this subject [2,3], which, amongst others, led to an advanced analysis procedure suitable to discriminate between influences of the thermal and optical properties of the sample [4]. Recent implementations of this technique utilize an IR-camera instead and moving the sample stepwise [5]. Such an approach opens up the possibility of applying data analysis and manipulations that work on the image plane of the resulting sequence of thermal images. Accordingly, procedures based on 2nd order spatial derivatives have been introduced [5] or compensations of global heating and blackbody effects [6]. Such an approach, however, requires long measurement times on the order of 1 s per scanning step and is not suitable for large and heavy samples due to the need for a mechanical scanner.

Alternatively, we proposed a method [7] using a continuously scanning laser together with a fixed IR-camera, similarly to the recent work of Burrows et al. [6]. Additionally, in order to enhance the quality of the crack images, we developed a robust and universal
algorithm based on 1st order spatial derivatives. Our approach requires no information on the scanning speed or path and even allows for testing bulky samples with curved surfaces.

![Diagram of experimental setup](image)

**Figure 1:** Sketch and photo of the experimental setup consisting of an IR-camera and a diode laser fibre-coupled to an optical scanner.

## 2. Experimental

For local heating we apply an experimental setup (see Fig. 1) consisting of a diode laser fibre-coupled to an optical scanner (920 nm wavelength, 93 W continuous wave output power, ~1 mm spot diameter, 20 m/s maximum scanning speed) and a fixed InSb-based IR-camera (640×512 pixel, 100 Hz frame rate, sensitive in the 3-5 µm wavelength range, 50 µm/pixel spatial resolution). The sample surface is successively scanned in parallel lines in the same direction in a lateral distance according to the laser spot diameter. The best results were obtained with a constant scanning speed of 20 to 100 mm/s, but, for larger cracks, speeds up to 10 m/s are possible as well.

As properly characterized test specimen, we chose a piece of used rail and an artificial steel test sample containing spark eroded notches (see Fig. 2). The rails bearing surface is densely packed with roll contact fatigue cracks (i.e., "head checks") with a typical length of less than 20 mm and an average separation to each other smaller than 4 mm. The rail is made of ferritic steel providing sufficient high permeability for magnetic inspection methods. As a reference method for the validation of our flying spot thermographic testing, we thus used magnetic particle inspection in magnetic flux mode according to DIN EN ISO 9934. To increase both the absorption coefficient for the laser radiation and the emissivity for the thermal radiation we applied a graphite coating to the rails surface.

In contrast and as a test for the applicability of our technique to highly reflective materials, we left the steel slab entirely uncoated. This sample has outer dimensions of 11×6×0.8 cm³ (width×height×thickness) and contains ten regularly spaced spark eroded notches (i.e., artificial perpendicular cracks) with lengths between 4.8 and 5.7 mm, depths between 10 µm and 2.24 mm and gapes between 82 and 810 µm.
Figure 2: (left) Photo of the rail (profile S54) test specimen coated with graphite. The measurement areas are indicated by dotted lines: A: 10×25 mm², B: 18×70 mm². (right) Photo of the uncoated steel slab with artificial spark eroded notches, clamped within the sample holder. The camera view on the photo is tilted to enhance the visibility of the artificial cracks.

2. Data analysis

Before the discussion of the developed crack detection algorithm, we point out the underlying physical mechanism giving rise to the thermal signature of the cracks. The best way to clarify this is to consider Fourier's Law

\[ \dot{q} = -k \nabla T = -R_{th} \nabla T, \]  

with the heat flux density \( \dot{q} \), the heat conductivity \( k \), the thermal resistivity \( R_{th} = 1/k \), and the temperature gradient \( \nabla T \). Given a constant heat flux density (that is induced by the laser), a localized thermal resistivity \( R_{th} \) like a crack leads to high value of \( \nabla T \). In the case of three dimensional heat conduction with a localized source the heat flux density is not constant and, in addition, affected by \( R_{th} \), but the qualitative prediction remains valid. Consequently, the higher thermal resistivity leads to a reduced cooling and thus to a higher maximal temperature when the laser spot is in the vicinity of a crack, eventually giving rise to the thermal crack signature.

The implementation of equation (1), making direct use of this fundamental relation, is schematically depicted in Figure 3. Per sequence image (see Fig. 3 b) we calculate the spatial derivatives in \( x \) and \( y \) direction, respectively (i.e., \( \nabla T = -R_{th} \dot{q} \)), displayed in Fig. 3(a,c). The temporal evolution of these derivatives for a single pixel in direct vicinity to a crack is shown in Fig. 3(d,e). Since the first derivation is sensitive to heat fluxes and thus thermal resistances in one direction only, we first concatenate both these sequences of derivatives to a single dataset which is then sorted at once (cf. Fig. 3 f). The first and last values represent the minimum and the maximum, respectively. These measurement points are recorded when the laser spot is positioned directly next to the crack. Sorting both first derivatives together automatically assures that the more sensitive one, thus revealing more extreme values, is selected. As a result, all crack indications are combined into a single image \( I_{res}(n) \).

Slightly better results in terms of visual resolution and signal-to-noise-ratio can be achieved by not selecting the first/last image but choosing data somewhat away from the extreme values (see Fig. 4 g for \( I_{res}(n=4) \)). We assume two main reasons for this behavior. Outliers due to noise, whose absolute values are increased by the derivation, are most likely to be included in the extreme images. And, even more importantly, the extreme value of a pixel
is reached when the laser directly illuminates that pixel. Hereby effects like dirt burned by the laser can lead to wrong indications. The information in a less extreme image is mainly governed by heat conduction effects due to the indirect excitation.

Figure 3: Sketch of the algorithm used for thermographic crack detection. The raw data (a) is spatially differentiated for each single frame (a, c) and then every pixel is sorted by its value (f). The resulting image (g) reveals clear indications for cracks.

3. Results and discussion

Figures 4 and 5 show the results of the proposed procedure for crack detection for the two test specimens. For the coated piece of rail (Fig. 4 a) we used a testing speed of about 50 mm²/s, a laser output power of 5 W, and a camera spatial resolution of 230 μm/pixel. For the uncoated steel sample (Fig. 5) we applied a testing speed of about 100 mm²/s, a laser output power of 93 W, and a camera spatial resolutions of 160 μm/pixel (Fig. 5 a,b) and of 35 μm/pixel (Fig. 5 c) respectively. Since the rail sample has been tested with magnetic particle inspection (Fig.4 b), we are able to compare our results to this independent reference. First of all, the shapes and positions of the cracks are in excellent agreement. The amplitudes in the thermal image are dependent on the cracks thermal resistivities (see Eq. (1)), which can be used to characterize its geometries – after calibration – by a more sophisticated approach [8]. The widths of the thermographic crack signatures are systematically larger than the traces from the magnetic particle inspection because of a thermal broadening and the IR-camera’s lower spatial resolution (230 μm/pixel in Fig. 4 a). This fact allows a distinction of cracks with distances of less than 1 mm but larger than about 0.5 mm, whereas the crack signatures given by the magnetic particle inspection lead to distinctly higher spatial resolutions. However, the
crack detectability is strongly varying and the noise is much larger in case of the magnetic particle inspection.

Figure 4: a) Result of the thermographic crack detection of the rail sample in area B of Fig. 2 (measurement time 30 s). b) Result of the magnetic particle inspection in the same area.

As a first proof of the applicability of our technique to highly reflective materials and as a quantification of its sensitivity, we present results for the steel sample with artificial cracks in Fig. 5. All cracks are visible, where the second (at x=15 mm) and the third (at x=23 mm) have the lowest amplitudes since they are the most shallow and narrow ones with depths of 10 and 30 µm and widths of 81 and 82 µm, respectively. Obviously, there is a correlation between the amplitude of the crack indication and the crack depths: the deeper the crack the higher is the amplitude. But if the cracks are to shallow they are not acting as effective thermal resistances anymore. In our case, the limit is about 10 µm. At x=40 mm there is a double crack that cannot be resolved using the raw spatial resolution (160 µm/pixel) of Fig. 5 a. Therefore we re-measured this region with an about 4.5-fold higher spatial resolution (the laser spot size of 1.3 mm in diameter was kept constant) and the result is shown in Fig. 5 c. The double crack in the centre of this figure consist of two individual cracks with widths of 95 and 97 µm and depths of 110 and 108 µm, respectively. They are approximately 200 µm apart from each other, which corresponds to six pixels on the camera detector.

A closer inspection of Fig. 5 reveals artifacts at the upper and/or lower edges of the crack indications, at most at the first crack in Fig. 5 a and the 4th crack in Fig. 5 b. So far we do not have a complete understanding of these artifacts. One possibility is that the laser directly couples into these cracks. Since both of them are relatively wide (larger or approx. 200 µm) and deep (on the order of 1 mm), they effectively form a cavity which results in a much higher absorption of the laser as compared to that of the sound regions. Consequently, this higher absorption results in a higher local temperature.

Another important aspect is how to select the best image from the sorted dataset. While the extreme value images reveal an increased noise level because they contain all statistic outliers the median value image is nearly homogenous. It can be stated, that it is safe to select the maximum image, while a subjective selection of the best image might slightly improve the result.
4. Conclusions

In conclusion, we presented a flying laser spot thermographic technique for the fast detection of surface breaking cracks. In contrast to the original flying spot camera concept, we apply solely commercially available components: a laser scanner and an infrared camera together with an innovative algorithm. This algorithm is based on first order spatial derivatives of the surface temperature after laser excitation and sorting of these derivatives together on an individual pixel basis. As a consequence, no information about the laser spot position or the scanning speed is needed. Furthermore, the technique is not affected by rounded surfaces like from the tested piece of rail and allows testing of difficult geometries without direct or even
close access, and it can be simply added to an existing thermography setup, without the need to synchronize the testing equipment. In addition, since the presented testing procedure only makes use of the thermal properties – like all classic thermography applications – it can be used for nearly all materials. Using two different test samples, a piece of rail with roll contact fatigue cracks and an uncoated steel slab with spark eroded notches, we demonstrated the feasibility of the technique. In case of the rail excellent agreement with standard magnetic particle testing is found and in case of the steel slab feasibility for highly reflective metallic surfaces is proven. As a result, with our approach it is possible to distinguish surface breaking cracks with distances on the order but larger than the camera’s spatial resolution, in our case at least 200 µm, - even with a distinctly larger laser spot size (here 1.3 mm in diameter). For the widths of the cracks this limitation does not hold. Here, cracks with widths smaller than the cameras spatial resolution are found, in our case < 100 µm, since our algorithm is based on the longer ranging temperature gradients induced by the laser. A particularly high sensitivity concerning the detection of shallow cracks is achieved. With the presented technique cracks with depths as shallow as ~10-30 µm are found.

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References