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Lock-in thermographic inspection of squats on rail steel head

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HIGHLIGHTS

- It is outlined the use of lock-in thermography process for detecting squats in track.
- The lock-in thermography results agree with the experimental observation.
- The reported method can be used to defect the location and the depth of squats.

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ABSTRACT

The development of squat defects has become a major concern in numerous railway systems throughout the world. Infrared thermography is a relatively new non-destructive inspection technique used for a wide range of applications. However, it has not been used for rail squat detection. Lock-in thermography is a non-destructive inspection technique that utilizes an infrared camera to detect the thermal waves. A thermal image is produced, which displays the local thermal wave variation in phase or amplitude. In inhomogeneous materials, the amplitude and phase of the thermal wave carries information related to both the local thermal properties and the nature of the structure being inspected. By examining the infrared thermal signature of squat damage on the head of steel rails, it was possible to generate a relationship matching squat depth to thermal image phase angle, using appropriate experimental/numerical calibration. The results showed that with the additional data sets obtained from further experimental tests, the clarity of this relationship will be greatly improved to a level whereby infrared thermal contours can be directly translated into the precise subsurface behaviour of a squat.

1. Introduction

Rail squats are found in rail heads all over the world due to increases in operating loads, traffic, and train speeds [1,2]. As indicated in [1], the sectioning and microscopic examination of the rails containing squat defects reveals the following main aspects: a ‘white etching’ surface layer (WEL) is present in most mild and moderate running surface squats, which can be up to 0.15–0.20 mm deep. The ‘white etching’ layer is brittle and develops small vertical cracks. Some of these cracks (at least initially) continue to grow into the parent material, both longitudinally and laterally, at an angle of about 10–30° to the running surface. Others return to the surface and form a spall and at a certain depth below the rail surface the cracks begin to branch and grow on multiple planes. Observed squats are non-planar 3D features that nucleate from areas of high stress concentrations in geometrically complex regions of the rail, see Fig. 1. It is vital to be able to detect squats before they reach this critical stage. Therefore the development of inspection methods to assess squat presence and measure their depths are of considerable interest.

Lock-in thermography utilizes a sinusoidal thermal stimulus to excite an object of interest. This stimulus can be introduced to the structure internally via thermo-elastic effect or by an external stimulus such as an array of heat lamps. When a photonic heating source is used in the lock-in technique, the technique is usually referred to as optical lock-in thermography. The phase angle refers to the measured phase difference $\Delta\phi$ between the sinusoidal input signal and the measured thermal signal response of an object. The use of lock-in thermography technique as a non-destructive evaluation technique is becoming increasingly attractive in the detection of surface or sub-surface defects in many diverse applications [3–8]. Lock-in thermography offers several advantages over other non-destructive techniques in that it is non-contact, able to inspect wide areas and produce easily interpreted results. The aim of this paper is to determine whether lock-in thermography can be used to firstly locate squats in rails, and secondly measure their depths. Lock-in thermography has demonstrated feasibility in generating thermal responses that could be adequately utilized for the purpose of defect characterization.

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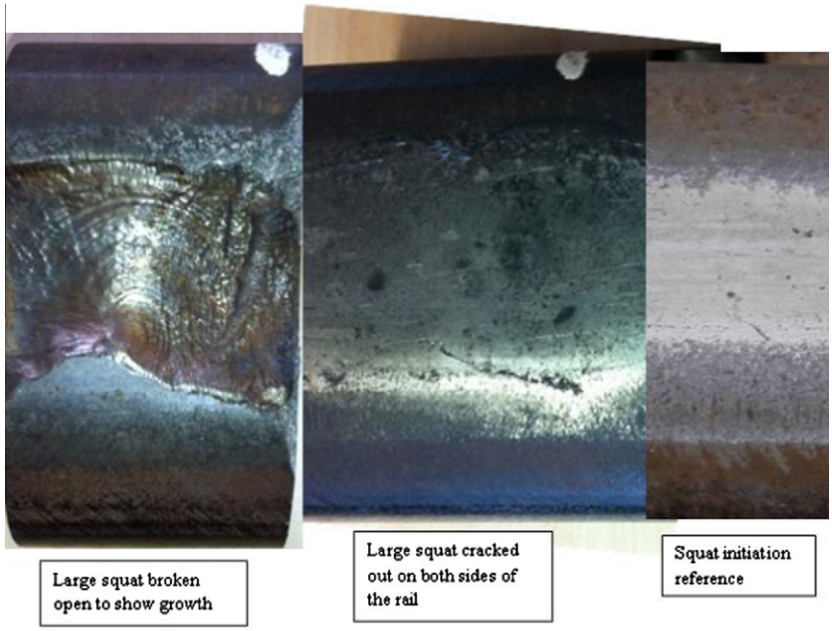

Fig. 1. Zoomed in view of the region of initial growth.

2. Experimental setup and thermography experiment

An infra-red camera (CEIP infrared systems) was placed 0.57 m above the surface of the rail sample. Four 750 W stage lights controlled by an agilent 3320A (20 MHz) function/arbitray waveform generator provided the sinusoidal heat flux at 0.2 Hz. Lock-in thermography works best if multiple periods are captured, as the phase angle data is effectively averaged. This way noise has been reduced thus minimising error from the results. The experimental setup for optical lock-in thermography is shown in Fig. 2. This frequency (0.2 Hz) was used as it is low enough to detect defects up to 8 mm deep [9], yet high enough to allow multiple periods to be measured in a reasonable time frame. Accumulation time was 30 s, thus allowing six periods to be captured. Thermal images are recorded at alternate phases (in this paper, we used three locations, S_1, S_2 and S_3), over a particular thermal cycle. The pixels phase and amplitude can be calculated using the selected phase locations through the following equations:

$$A(n) = \frac{2}{3}\sqrt{S_1^2 + S_2^2 + S_3^2 - S_1S_2 - S_2S_3 - S_3S_1} \quad (1)$$

$$\phi(n) = \tan^{-1}\left[\sqrt{3}\,\frac{S_1 - S_3}{2S_2 - S_1 - S_3}\right] \quad (2)$$

When processing the results from the experiment, the phase angle from the edge of the squat was used when finding phase contrast, as this was deemed the deepest part of the squat and was presumed to be the depth corresponding to the ultrasonic data.

Lock-in thermography tests were carried out on specimen (marked ‘Sample 6’) that had already been tested ultrasonically by Railcorp [10] and had their squats marked and depths recorded. The phase images produced from the lock-in thermography experiment successfully showed the presence of squat defects in the rail sample. All squats found by Railcorp were visible in the phase images. The phase contrast at that precise point was then recorded for each squat and plotted against its depth, as measured physically. Also, the phase contrasts were graphed along the length of the cut for these squats, see Figs. 3–8.

To quantitatively analyse subsurface features, it was necessary to do ‘calibration study’. This explores the effects that various factors, such as defect size and crack profile shape, have on the thermal response. It can be performed by experimental pre-tests or numerical modelling with necessity for (artificial) representations of a defect. Both a 3D finite element modelling (FEM) and pre-test experiment were used to generate a ‘calibration curve’ that would relate phase contrast to squat depth, so that anyone who conducted a lock-in thermography experiment on rail squats could determine their depths based on the phase images.

Fig. 2. Experimental setup of the lock-in thermographic equipment and specimen.