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Laser ultrasonic characterisation of branched surface-breaking defects

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ABSTRACT

Surface-breaking defects often have a geometry which is more complicated than the 'normal slot' used in many calibration tests, and this geometry will affect the reflection and transmission of ultrasonic surface waves incident on the defect. We present here measurements on defects with varied branched geometries, designed to simulate stress corrosion cracking (SCC) type defects, characterising the geometry using laser-based ultrasonic generation and detection of Rayleigh waves. We show the behaviour of the near-field enhancement and the far-field reflection as a function of branch position and length, and signal analysis which can be used to gain further information for characterising the defect geometry. The experimental results and finite element method (FEM) models presented in this paper highlight the potential of this technique to test components prone to developing SCC, in order to identify and characterise surface-breaking defects.

1. Introduction

Stress corrosion cracking (SCC) is a form of corrosion which produces a marked loss of mechanical strength with little metal loss [1,2]. The cracking typically grows in a branched manner into the sample, and is often surface-breaking. Damage produced by this type of cracking might not be obvious to visual inspection and, if it goes undetected, can trigger mechanical fast fracture of components and structures [1,2]. Therefore early assessment and characterisation of such material defects is of great importance, in order to have sufficient time for adequate measures to be taken to either restore or replace the endangered component. New non-destructive testing techniques are under development for this purpose, with methods being developed for both in situ and remote testing [3–7].

Several non-destructive testing techniques are currently used to detect surface-breaking defects, for example dye penetrant, magnetic particle inspection, and eddy current testing, amongst others [4,8,9]. However, internal geometry visualisation and characterisation of such defects is currently only possible with radiographic methods [10]. Amongst these methods, X-ray microtomography excels where high resolution information is needed in three spatial dimensions [5,11]. However, radiation-based techniques are costly and normally require a section to be removed for inspection, which is not practical for routine testing. Ultrasonic testing shows some promise for characterisation, and simulations have been implemented to quantitatively predict the diffraction echoes of bulk waves by complex defect geometries (e.g. irregular, multi-faceted notches or branched defects), when using time-of-flight diffraction or the pulse-echo ultrasonic technique [6,7].

Ultrasonic testing techniques using surface acoustic waves (SAWs) may potentially be an alternative to radiographic methods for routine inspection of these defects. It has been shown that changes in the reflection and transmission of SAWs can be used to gauge the overall defect depth for simple calibration defect geometries (e.g. defect simulated as a slot, normal to the sample surface) [12–15]. This research has primarily focused on the measurement and understanding of SAW scattering effects in the far-field (i.e. detection probe placed at distances far from the crack), however, research has also looked at understanding the behaviour of SAW scattering in the near-field (i.e detection probe placed in the immediate vicinity of the crack) [15–20]. The benefits of probing interactions in the near-field include enhanced signal levels and sensitivity to local features, and the use of lasers for generation of ultrasound has been shown to be sensitive to partially closed cracks [3,21]. These near-field studies look at the increase in amplitude (enhancement) of the SAW very close to the defect due to the constructive interference of reflected and mode-converted waves, and have been studied in both the time and the frequency domain [15,19,22].

The interaction of Rayleigh waves with more complicated defect geometries has focussed on angled defects of finite depth [22–24], and has shown that the reflection and transmission of Rayleigh waves are angle dependent. The near-field enhancements in both the amplitude and frequency content have been used to identify and find the angle orientation with respect to the surface [22,25,26].

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In this paper we explore the effect of SCC-like branched defect geometries on SAWs, and show the near-field enhancement and the far-field reflection and transmission as the branch position and length vary. Results from experimental measurements and finite element method (FEM) models are presented. The near-field enhancement, arrival times of the reflected and transmitted waves, and the frequency content of the reflected wavemodes, are used together to characterise the crack geometry.

2. Experimental setup and FEM model

Laser generation and detection were used to investigate the interaction of Rayleigh waves with different machined defects on a set of aluminium samples. Fig. 1 shows the experimental setup used, with the samples of dimensions $50 \times 50 \times 150\ \text{mm}^3$ containing branched defect geometries manufactured using electrical discharge machining. These defects are comprised of slots machined straight down into the sample, which have a constant length ($d=2$ mm), with a branch of various lengths ($x=0.25-2$ mm) propagating at 45° to the sample surface, starting at either the opening or half way down the slot. The samples were designed to simulate one of the properties of SCC, namely branching, to add complexity above that of typical calibration slots.

Experiments were performed using a pulsed Nd:YAG laser source (2 mm spot size, 1064 nm wavelength and 10 ns pulse duration) to generate Rayleigh waves. The laser beam was filtered in order to generate in the thermoelastic regime, to avoid damaging the samples [27]. Signals generated were broadband, covering a range of approximately 50 kHz–1.5 MHz, with a maximum at 400 kHz. For detection, a two-wave mixer laser interferometer from Intelligent Optical Systems was used. The interferometer measures the out-of-plane displacement, and has a 200 μm diameter detection spot-size and a bandwidth of 125 MHz. The power of the continuous wave probe laser is variable up to 2 W, dependent on the sample surface quality, and is able to measure on rough surfaces without the need for surface preparation such as polishing [28], which is required when using homodyne or heterodyne reference-beam interferometers with coherence detection.

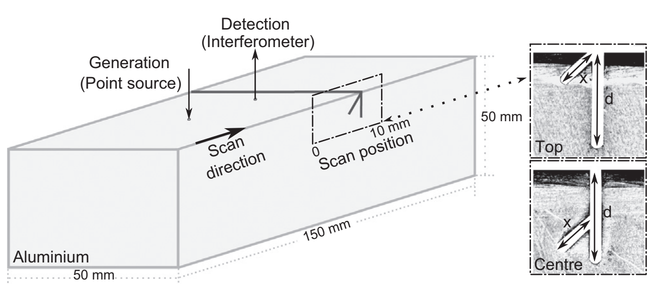

Fig. 1. Experimental setup used for inspection of samples containing branched defects with the geometry shown.

Measurements were carried out by keeping a fixed separation between the generation source and the detection point, and scanning in steps of 0.05 mm such that the detection point passed over a region of the sample running from 5 mm before to 5 mm after the slot, as shown in Fig. 1. The out-of-plane displacements were recorded after averaging of 64 data samples for each detection position.

FEM simulations in the time domain were performed using PZFlex, a wave-propagation analysis software designed for ultrasound applications [29]. A two-dimensional model geometry with appropriate boundary conditions was used; all surfaces apart from the top were assigned to be 'absorbing', to reduce interference of the Rayleigh wave signals with waves reflected from the sample sides and bottom. The absorbing boundaries in PZFlex act to reduce the amplitude of these reflections, approximating a half-space, but not completely absorb them. The mesh used was a square mesh, with 124 elements per wavelength, calculated at the central frequency of the pulse. To simulate the laser generation a dipole force was applied onto a region of the top surface 30 mm away from the defect. In order to decrease the simulation runtime, and in contrast to the experimental case, the generation source was kept stationary while the detection point was scanned in steps of 0.05 mm to cover the same region of the sample as in the experimental measurements. Due to the varying separation used in the simulations, the arrival times for the ultrasonic waves differed from the experimental measurements.

3. Results

Fig. 2 shows B-scans produced during experimental scans of two samples (both with a branch of 1 mm length, propagating from either (a) the top, or (b) the centre of the 2 mm deep slot), where the amplitude of the signals is shown by the colour scale and the defect opening is at a position of 5 mm. The colour scales used in Figs. 2 and 6 are set so that black shows large negative displacements while white shows large positive, with the same scale used for all subplots in each figure; the actual values are arbitrary as these figures are for identification of modes and arrival times. For both geometries there is a clear incident Rayleigh wave (feature around 18 μs in (a), and 20 μs in (b), with the different time due to slightly different experimental set-ups), with various reflected and transmitted waves also present. At the defect the incident Rayleigh wave and any reflected or mode-converted waves interfere, and where there is constructive interference an enhancement of the signal amplitude will be observed [15,30];

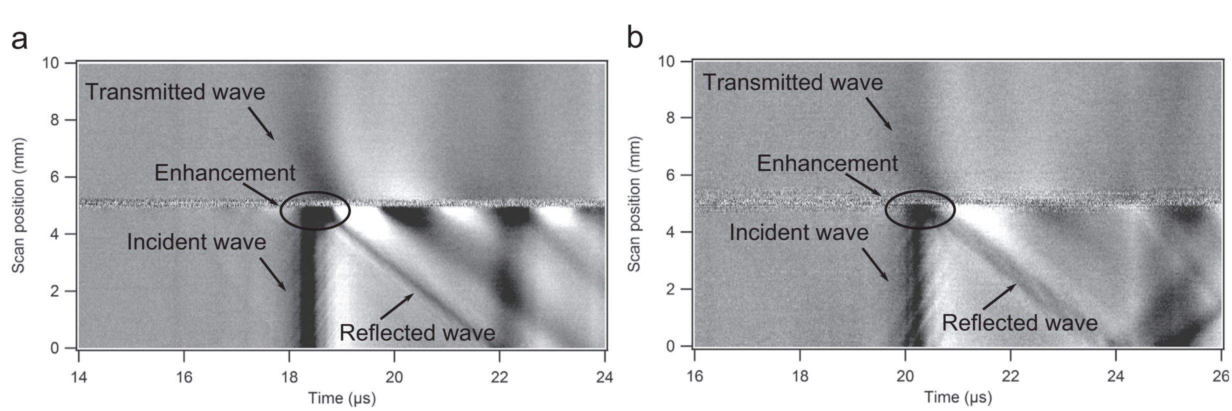

Fig. 2. Experimental B-scans showing the out-of-plane displacement of the Rayleigh wave as it interacts with a branched defect. The branch length is 1 mm, positioned either at (a) the top or (b) centre of the slot.