Corrosion Science 78 (2014) 335–342

Contents lists available at ScienceDirect

Corrosion Science

journal homepage: www.elsevier.com/locate/corsci

Stress corrosion cracking detection using non-contact ultrasonic techniques

F. Hernandez-Valle, A.R. Clough, R.S. Edwards *

Department of Physics, University of Warwick, Coventry CV4 7AL, UK

A R T I C L E I N F O

Article history:
Received 17 May 2013
Accepted 12 October 2013
Available online 24 October 2013

Keywords:
A. Stainless steel
C. Stress corrosion

A B S T R A C T

In this work a method is presented for detecting and locating stress corrosion cracking (SCC) in stainless steel pipe samples. The method combines laser generation and either laser or electromagnetic acoustic transducer (EMAT) detection, scanning the generation point across the sample surface. Using laser-generated ultrasonic waves that interact with the cracks, and performing time–frequency analysis techniques to examine changes in the generated wavemodes, surface plots that clearly resolve the spatial extent and geometric alignment of the cracks are created and presented here. The method is demonstrated using components removed from service after exhibiting SCC.

1. Introduction

The interaction of a corrosive environment and tensile stress (e.g. directly applied stresses or in the form of residual stresses) can produce failure in the form of stress corrosion cracking (SCC) in susceptible metallic components [1]. The damage produced by SCC is not always obvious to casual inspection, so failure can be both unexpected and catastrophic. Thus, early detection of such defects is important in order to have sufficient time for adequate measures to be taken, for example repair or replacement of the damaged component.

Various nondestructive evaluation (NDE) techniques have been trialled to detect and locate this type of cracking, all with certain advantages and disadvantages. For example, dye penetrant testing is a widely used and relatively simple method which can be easily performed at remote test sites. However, besides requiring surface preparation, dye penetrant can only detect defects that are open at the sample surface, and it performs poorly on hot, dirty, and rough surfaces as well as on porous materials [2,3]. Eddy current and pulsed eddy current techniques can be used for rapid inspection, and have a relatively small probe size, and there is no need to physically contact the test samples. However, eddy current inspection only detects surface or near-surface defects, it is very sensitive to a wide range of parameters related to the conductivity and magnetic permeability of the test sample, and is very sensitive to lift-off variations [4–6].

Radiographic inspection has the advantage over many other NDE techniques in that analysis and interpretation is almost intuitive. Amongst radiographic methods, X-ray tomography excels where information is needed in three spatial dimensions [7–9]. However, despite the advantages, radiation techniques have serious safety concerns due to possible overexposure to large amounts of radiation. In addition, a closed crack will generally only be detectable in a radiograph at certain orientations, ideally when the long dimension of the crack is parallel to the direction of radiation propagation [7–9].

Various ultrasonic techniques have been used for SCC detection, in particular time of flight diffraction (TOFD). This technique relies on the detection of weak diffracted waves arising at the edges or tip of a crack, and can locate and size defects either within the bulk of a sample, or on the surface [10,11]. Although TOFD is well understood and widely used it has some limitations, such as the assumption that there is no interference from other wavemodes. In some geometries this will limit its applicability to cases where there is only a single defect, thus research to add new features and remove some limitations is still being performed [10,11].

Standard ultrasonic measurements, particularly those looking for reflections of bulk waves from defects, have difficulties due to the low reflection and transmission coefficients for closed and partially closed defects. However, recent work looking at the interaction of surface waves with surface-breaking defects in the near-field have shown several enhancement mechanisms which can be used for identification of cracking [12–20]. For Rayleigh wave propagation on thick samples, the signal enhancement observed when scanning the detector across the crack is due to

---

* Corresponding author. Tel.: +44 2476 523393.
E-mail address: r.s.edwards@warwick.ac.uk (R.S. Edwards).

0010-938X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.corsci.2013.10.018

the constructive interference of incident, reflected and mode-converted waves [12,13,15]. For defects propagating at an angle to the surface, where the local thickness changes throughout the defect, further large enhancements are also seen in the time and frequency domains [21–23]. Similar effects are seen when scanning thin samples using Lamb waves, with enhancements observed as an increase in magnitude of the signal at certain frequencies [24]. These distinctive features can be used to identify the defect and give some information about its geometry [23].

For laser generation, further enhancement effects have been observed due to the changes in generation conditions when the generation spot is over a defect [18–20,25]. As the laser spot passes over the defect, the boundary conditions of generation on the surface will change, and this has been shown to give an increase in the magnitude of the signal at certain frequencies. If the defect is partially closed and the laser spot source is directly illuminating the defect, then the material will also undergo thermo-optic crack closure, which has been shown to produce higher order frequency components [20].

In this paper we examine the near-field interactions of laser generated ultrasonic waves with stress corrosion cracking in stainless steel pipe samples removed from service, and use the ultrasonic signal enhancement to resolve the spatial extent and geometric alignment of those cracks. Ultrasonic waves generated in bounded media, such as pipes, take the form of guided waves. These travel along the pipe with different propagation and displacement behaviour depending on the particular wavemode (e.g. longitudinal, torsional or flexural modes in pipes, and higher-orders of each of these) [26]. The particular wavemodes generated depend on the pipe geometry, the material, the generation source used and also the testing frequency. Quantification of the enhancement effect for guided waves in the time domain is complicated due to the presence in most cases of more than one wavemode, thus time–frequency analysis is performed in order to highlight which modes were generated and/or enhanced [19].

The generation of ultrasound here was performed using a thermoelastic laser source, described in Section 2. For detection two different approaches were used; laser interferometry techniques (Section 3.1) or electromagnetic acoustic transducers (EMATs, Section 3.2). Both approaches are non-contact, and hence their influence on the sample properties and on the wavemode being measured is negligible [27]. Both can easily be scanned across the sample surface, and can work on rough surfaces and in hostile environments. Laser detection has the advantage of high spatial resolution, which adds to the accuracy of defect location. However, laser detection systems are still a costly option when compared to the EMAT detection approach.

The paper is organised as follows. In Section 2, a description of the experimental setup and time–frequency analysis are given. Results from scans of damaged pipe samples and discussion of each detection approach are given in Sections 3.1 and 3.2. Finally, a summary of the uses of these approaches is presented in Section 4.

2. Experimental method

Experiments were performed using a pulsed Nd:YAG laser (1064 nm wavelength and 10 ns pulse duration) to generate ultrasound, focused into a point of approximately 500 μm diameter. The laser was filtered such that it acted in the thermoelastic regime, minimising damage to the sample, to generate broadband ultrasonic waves [28]. In this regime, the area impinged by the laser beam is heated rapidly, expanding and generating stress as the surrounding cooler material constrains its expansion. The associated pulse of material expansion and contraction can generate a range of ultrasonic modes, such as bulk longitudinal and shear waves, or Rayleigh waves and other guided wave modes, depending on the sample geometry. For detection, to investigate the near-field interactions of surface acoustic waves with SCC, two different approaches were used; laser detection, or EMATs [27].

For laser detection, a two-wave mixer laser interferometer system from Intelligent Optical Systems [29] was used (setup shown in Fig. 1a). The interferometer is sensitive to the out-of-plane component of the surface displacement, and has a bandwidth of 125 MHz, allowing measurements over a wide range of frequencies. Its continuous wave laser (200 μm spot-size) operates at 1550 nm, with a power variable up to 2 W; this is varied depending on the sample surface quality. The interferometer works on rough surfaces without the need for surface preparation [29].

For EMAT measurements, linear detection coils were used, produced by wrapping 10 turns of 0.08 mm diameter insulated copper wire around NdFeB magnets of field approximately 0.5 T, with the field aligned either into the sample, for measuring predominantly in-plane particle velocity, or along the sample surface for measuring predominantly out-of-plane velocity. The transducer active measurement area was 1 mm (width) by 35 mm (length). For a description of the principle of operation and more detailed description of the EMATs used, the reader is referred to Ref. [23].

Measurements presented here were done on two different AISI 304 stainless steel sections of pipes removed from service. Both pipe sections had an inner diameter of 152.4 mm and an outer diameter of 160.2 mm, and hence a wall thickness of 3.9 mm, with different axial lengths; 270 mm (sample A) and 50 mm (sample B, see Fig. 1b). Sample A contained two cracks (SCC 1 & SCC 2) and some pitting damage in the region of interest (Fig. 4a), whereas sample B contained several features which looked like surface-breaking cracks to visual inspection (Fig. 5a).

Regardless of the detection technique, the scanning process consisted of placing each sample on a rotational stage to perform a circumferential scan, such that the generation laser source passed over the region of interest with constant steps; these increments correspond to the *x*-axis on the surface plots shown in Figs. 4, 5, and 10. The vertical position of the generation and detection points was then varied, starting from the lowest part of the region of interest and moving up until reaching the upper part with increments of approximately 2 mm; these increments correspond to the *y*-axis on the surface plots.

Guided ultrasonic wave modes were generated, propagated along the sample, and were detected by the laser or EMAT. Since guided waves in pipes can consist of several different wavemodes, with those present depending on the pipe geometry, the frequency of the ultrasonic wave and the generation source [26], mode identification using just the signals in the time domain is complicated. For this reason, a time–frequency analysis was performed on each A-Scan at each scan point to identify the arrival time of each frequency component, and to highlight which modes were generated and/or enhanced (see Figs. 2, 6 and 7) [19,24,30]. Each wavemode has a frequency-dependent velocity which can be calculated, and hence the sonogram analysis used here is able to identify modes based on their arrival times, and allow identification of modes which show sensitivity to the presence of a surface-breaking defect. An increase in the magnitudes of these modes at a defect can then be measured through windowing the correct region of the sonogram, and used for the construction of surface plots that resolve the spatial extent and geometric alignment of SCC in the pipe's surface.