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Scanning laser source Lamb wave enhancements for defect characterisation

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ABSTRACT

Surface-breaking defects in thin storage structures can cause costly component failure if left undetected. Here, a method for detecting and characterising surface breaking defects using near-field Lamb wave enhancements is presented for measurements in which a laser generation source passes over the defect. A dual laser scanning system is used to generate and detect Lamb waves in aluminium plates containing v-shaped laser micro-machined slots of different depths. Time–frequency analysis techniques are used to identify and track the magnitudes of individual wave-modes across a scan at different frequencies, and large enhancements in signal magnitude at certain frequencies are observed for the fundamental A0 and S0 wave modes when the laser source passes over the defect lip. The mechanisms responsible for this enhancement are identified and examined, and a characterisation process for identifying the position and severity of the defect is presented.

1. Introduction

The early detection and characterisation of defects within a structure is of great interest to industry as a means of preventing component failure, which can have costly economic and environmental impacts. Of particular interest is the early detection of surface breaking defects in storage and transport structures, in which crack formation can rapidly lead to full structural failure, thereby allowing leakage of the hazardous or valuable material into the environment [1,2]. One mechanism by which problems occur is stress corrosion cracking (SCC), which involves the growth of a defect from the surface of a component placed in a corrosive environment whilst that component is under stress, and SCC is of particular concern to the nuclear industry, amongst others [1,2].

The branched nature of stress corrosion cracks can lead to complicated reflection and transmission patterns, with associated difficulties in explaining the physical phenomena observed. Recent work has used a surface breaking v-shaped slot to mimic the opening mouth of a SCC defect, and this has been used successfully to obtain an understanding of the interaction between an incident surface ultrasonic wave and a surface breaking defect [3–5]. Research has also been carried out using square based notches to simulate surface-breaking defects, with a focus on the reflection and transmission characteristics of the defect [6–8].

The reflection and transmission behaviour of surface acoustic waves at surface breaking defects in thin samples has previously been used to characterise the position and/or depth of these defects, using a guided wave approach [9–12]. This allows for long range inspection of components with wave propagation distances of several metres. However, this method can be limited by the presence of multiple wave-modes, and resolution can be limited if defects are located close to one another or have insufficient depth to cause a significant reflection of the incident wave [8]. Experimental techniques based on the pulse-echo technique have also been employed for surface defect detection [13], however, problems can occur due to the overlap of multiple reflections. These approaches utilise measurements in the far-field of the defect, following interaction of the wave with the defect; however, there has been much recent interest in the phenomena that occur in the near-field (here the near-field refers to the defect not to the transducer as is commonly used), and the use of this to position and characterise defects, thereby avoiding problems due to overlapping arrival times or defects in close proximity to one another [3–5,14–18].

2. Background

Ultrasonic enhancement is a phenomenon in which the amplitude and frequency content of a surface wave experiences a large increase, when the generator or detector is scanned over a surface-breaking defect. The enhancement of Rayleigh waves in the near field of a defect has previously been exploited for defect detection and characterisation when either a laser detector [5,4,16] or a laser source [4,14,15,17] is passed over the defect, in a similar fashion to the

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method shown in Fig. 1 but for samples where thickness > wavelength (λ). Scanning laser detection involves the detector being moved over the defect opening, with the laser source located away from the defect, allowing for the interactions of the incident wave with the defect to be studied as they occur. For the scanning laser source method the generation source is scanned over the defect, with the detector located away from the defect, allowing for the study of the behaviour of the ultrasound under changing generation conditions [14,17,19]. The enhancement manifests as a significant increase in the amplitude of the Rayleigh wave, and a corresponding shift in the Rayleigh wave centre frequency. It has been shown that these are related to the defect depth and its angle to the surface, with the enhancement used to position the defect [5,14,16,20].

For a sample of sufficiently small thickness, the dominant wave that is detected on the surface of the plate is a Lamb wave, which for any given frequency-thickness product can support two different types of wave-modes simultaneously: symmetric and antisymmetric [21]. Multiple higher order wave-modes can be supported above the frequency-thickness threshold for each individual mode, leading to the propagation of multiple wave-modes simultaneously, the velocity of which is dependent upon their frequency-thickness product (Fig. 2a) [3,21,22]. Near field enhancements have also been reported to occur during the interaction of Lamb waves with surface breaking defects for scanning laser detector measurements. The Lamb wave detection enhancements have been used to characterise the depth of v-shaped surface breaking defects in thin sheets in which the thickness is $<\lambda$ [3].

The enhancement when the detector is passed over the defect has been explained by a constructive interference between the incident wave and waves reflected or mode converted from the defect, for both Rayleigh and Lamb waves [3,16,20]. For Rayleigh wave measurements the observed enhancements show as an increase in the peak-to-peak wave amplitude, caused by the coincident arrival at the detector of the incident Rayleigh wave, a reflected Rayleigh wave and a mode converted surface skimming longitudinal wave which is generated from the interaction at the defect opening. A superposition of these waves leads to an increase in the surface displacement, the size of which depends on the depth and the angle to the surface of the defect, as these factors affect the extent to which reflection and mode conversion occur [4,5,16,20].

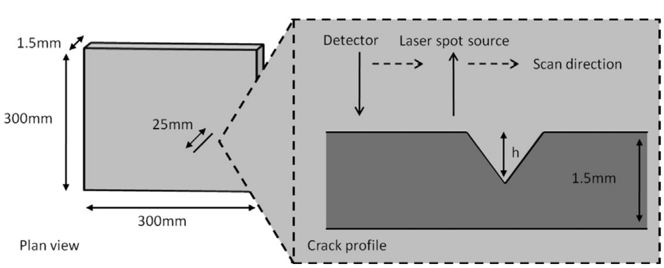

Fig. 1. Experimental setup for inspection of v-shaped surface breaking defects in aluminium sheets, showing the dual laser scanning movement.

A similar mechanism has been shown to be responsible for the scanning detector enhancements observed in Lamb wave supporting samples, in which a superposition occurs of the incident wave-mode, a reflected wave of the same mode, and other wave-modes generated on reflection of the incident wave-mode at the defect. The enhancement was examined for individual Lamb wave-modes, and the extent to which an enhancement occurs was shown to be dependent upon the amount of reflection and mode conversion occurring at the defect, dependent upon the defect depth, geometry, and the number of wave-modes supported at the given frequency-thickness. The total enhancement measured using scanning laser detection also depends on the distribution of the energy between the in-plane and out-of-plane directions, leading to some wave-modes experiencing higher levels of enhancement than others [3,21].

Scanning laser detector enhancements have been successfully used to give the position and severity of surface breaking defects. However, it has been observed that scattering from rough or partially closed defects makes this method insufficient on its own to fully characterise a defect [4,14,23]. With a two-laser scanning system it is possible to use enhancements from both the detector and the source in tandem to fully characterise a surface breaking defect.

It is known that changes in the generation conditions in the vicinity of a surface-breaking defect when using scanned laser source measurements will change the properties of the generated Rayleigh wave on thick samples [14,15,17,24,25]. Similar behaviour occurs for Lamb wave generation, and in this paper we examine the near field interactions of the fundamental Lamb wave-modes with a surface breaking defect as the source passes over the defect. Recent work has investigated laser scanning techniques using thermography, and electromagnetic acoustic transducers (EMATs) sensitive to the in-plane velocity component of the ultrasonic signals [25]. A change in the laser source beam shape was shown to occur during interaction with the defect, thereby altering the boundary conditions of generation. An enhancement in the frequency content of the in-plane component of the Lamb wave was observed at the position at which the source is directly over the defect [22], analogous to the amplitude enhancement observed in Rayleigh wave experiments.

In this paper we report near-field enhancement of Lamb waves. The increase in the frequency content of Lamb wave-modes in the near-field of a surface breaking defect is used to measure the position and depth of the defect. To resolve the individual Lamb wave-modes and understand the origin of the signal

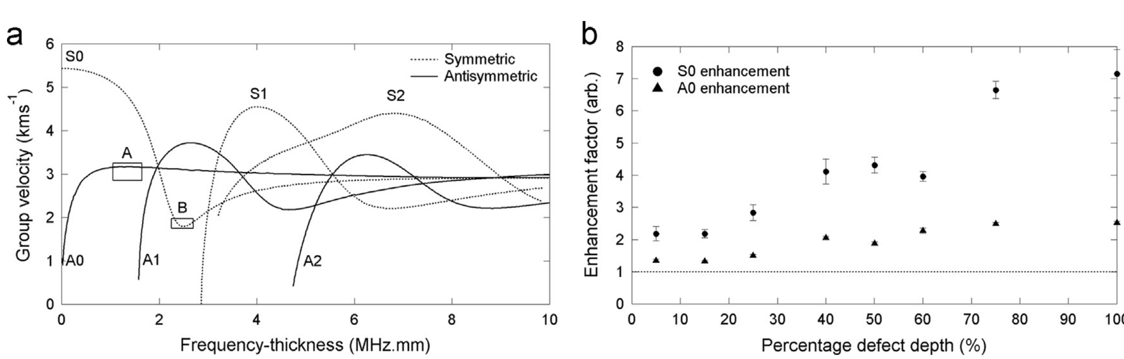

Fig. 2. Dispersion curves (a) for Lamb waves supported in a 1.5 mm thick sheet, with outlined regions of interest (A and B) and the variation in the enhancement factors corresponding to these regions as a function of defect depth (b).