Applied Acoustics 145 (2019) 1–6

Contents lists available at ScienceDirect

Applied Acoustics

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

Inspection of cracks with focused angle beam laser ultrasonic wave

Dongchi Yi, Cuixiang Pei *, Tianhao Liu, Zhenmao Chen

State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University, Shanxi Engineering Research Center of NDT and Structural Integrity Evaluation, Xi'an 710049, China

ARTICLE INFO

Article history:
Received 23 April 2018
Received in revised form 9 September 2018
Accepted 16 September 2018

Keywords:
Laser ultrasonic testing
Focused wave
Angle beam
Inner crack
Arc-line laser

ABSTRACT

In this work, in order to improve the detecting ability of laser ultrasonic testing technique for inner cracks in metals, an arc-line-focused laser source is proposed to generate focused angle-beam bulk waves in thermoelastic regime. The arc-line-focused laser source is achieved by passing an expanded and collimated laser beam through a convex and axicon lens off-center. The distribution of the shear waves generated by the arc-line laser source were detected by a laser interferometer to evaluate the focal area. Finally, the measurement of artificial cracks at the bottom surface of aluminum specimen with using the focused angle-beam bulk waves is investigated by experiment.

1. Introduction

Ultrasonic testing (UT) is one of the most important non-destructive testing (NDT) methods for material characterization and defect inspection in industries. Angle-beam UT method that directs bulk wave energy into the test pieces at a selected angle is particularly useful for far-surface defect interrogation [1]. Presently, angle-beam UT is mainly realized by using a wedge coupled to piezoelectric transducer. However, the requirement of acoustic coupling between piezoelectric transducer and test pieces in the traditional UT technique makes it difficult or even impossible to apply in some areas, such as hot environments, or on complex-shaped or fast-moving components.

As a new member of ultrasonic family, laser ultrasonic testing (LUT) provides a remote, wideband and controllable generation and detection of ultrasonic waves in materials. Due to such a unique superiority, it has become a very promising and desirable non-destructive testing method in many application areas [2,3]. However, one of the principle disadvantages of LUT is the low signal strength of the bulk waves in metal materials generated in thermoelastic regime. To improve the generation efficiency of the laser ultrasound without ablation damage on material surface, there have been some researches on designing laser patterns spatially or (and) temporally. For example, Marie-Helene et al. developed the laser pattern temporally and performed a set of rectilinear phased array laser sources on the specimen surface to generate focused bulk waves with an angle in the specimen [4–7]. However, this technique based on phased array method is relatively complex and costly, because an array of laser source or an optical fiber phased array is needed. In others researches, the laser pattern has been designed spatially by changing the focused shape of the incident laser. For examples, P. Cielo et al. presented a converging-wave approach with using a ring-shaped laser source. The point-focused surface wave or bulk waves could be detected at or under the center of laser ring [8–12]. However, this measurement mode is not suitable for angle beam inspection.

In this study, an arc-line-focused laser source realized with a set of optical lens is proposed to focus the generated angle beam shear wave at a focal point for crack inspection. The signal-to-noise ratio (SNR) and spatial resolution can be improved, making detection and evaluation of small crack possible. To verify the performance of this method, the distribution of the shear waves generated by the arc-line laser source were measured by a laser interferometer to evaluate the focal area. Finally, the focused angle beam shear wave was used to measure the inner cracks (the cracks are at the bottom of the specimen) varied in both length and depth by looking for reflections corresponding to cracks.

2. Measurement method and experiment setup

2.1. Principle and measurement method

When the ultrasound bulk waves induced by a point-focused or line-focused laser source in metal in thermoelastic mode, the bulk

* Corresponding author.
E-mail address: pei.cx@mail.xjtu.edu.cn (C. Pei).

https://doi.org/10.1016/j.apacoust.2018.09.012
0003-682X/

waves shows directivity [13,14]. As shown in Fig. 1(a), the amplitude of shear wave shows a sharp peak at about 30° normal to the metal surface, beyond which the amplitude drops quickly. In contrast, the amplitude of longitudinal wave shows a peak at about 65° [13,15]. Fig. 1 (b) shows a schematic explanation of the relationship between the focal point and the shape of arc-line laser source. Point A (0, 0, Z_{FL}) and point B (0, 0, Z_{FS}) are the location of the focal points of longitudinal wave and shear wave, respectively, R the radius of the arc-line laser. Comparing with the conventional line-focused laser, the arc-line laser produces longitudinal wave and shear wave converging towards to the focal points at a certain depth down the central axis, respectively. Therefore, the arc-line laser can give a more efficient way to detect the inner cracks. Because the thermoelastically generated longitudinal wave is much weaker than shear wave in metal [13], the shear wave is studied for inner crack inspection in this work.

The method of inner crack inspection with focused angle beam laser ultrasonic wave is shown in Fig. 2. When the arc-line laser is irradiated onto the surface of the specimen, the shear wave generated by the arc-line laser are point-focused at the bottom of the specimen with an angle. If there is a defect near the focal point, according to Snell's law, the ultrasonic beam would be reflected upward at the same angle and can be detected with a probe laser on the surface nearby. As the shear wave is focused, more wave energy could be reflected by a small crack, and the spatial resolution could also be improved. By moving the lasers parallel to the crack, the length of crack can be measured.

2.2. Experimental system setup

A schematic of the experiment system and the detail of its focusing objective are shown in Fig. 3. A pulsed laser beam with duration of 10 ns, wavelength of 1064 ns and pulse energy of 10 mJ generated by a Nd:YAG laser is firstly expanded and collimated with using a concave lens (with focal length of 50 mm) and convex lens (with focal length of 75 mm). The expanded beam is then passed through a combination of a convex lens (with focal length of 100 mm) and axicon lens (with physical angle of 10°). Then, an arc-line-focused laser source is generated on the specimen surface with shifting the laser beam off the axis of the focusing objective. The arc angle of the arc-line-focused laser can be changed continuously from 360°to near 0° by increasing the off-center distance between the center of laser beam and the axis of the focusing objective. A laser interferometer based on Two-Wave Mixing with bandwidth of 200 MHz is used to measure the surface displacement associated with the generated ultrasonic waves. The probe laser with wavelength of 532 nm from the interferometer is reflected by a dichroic mirror and focused to a point near the arc-line focused laser on the specimen surface. The oscilloscope with signal averaging (16×) is used to record the ultrasound signals detected by the interferometer for an improved SNR. The computer containing the stage control and signal processing software is used to capture and process the data obtained from the oscilloscope.

3. Measurement results

3.1. Focal area of shear waves

Before the application for crack inspection, the focal area of the shear wave generated by the arc-line-focused laser is measured firstly. The measurement setup is shown in Fig. 4, the top surface of an aluminum plate (15 mm thick) is irradiated by an arc-line-focused laser. The radius of the arc-line-focused laser is

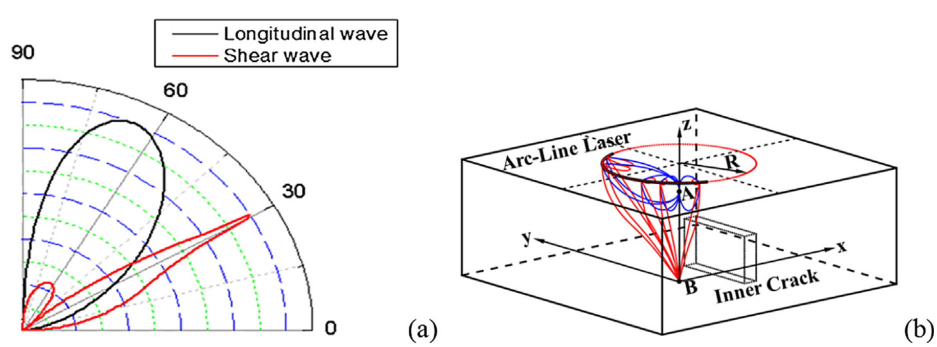

Fig. 1. The relationship between the focal points of bulk waves and the shape of arc-line laser source: (a) directivity of bulk waves in thermoelastic mode, (b) schematic of the convergence of bulk waves generated by the arc-line laser.

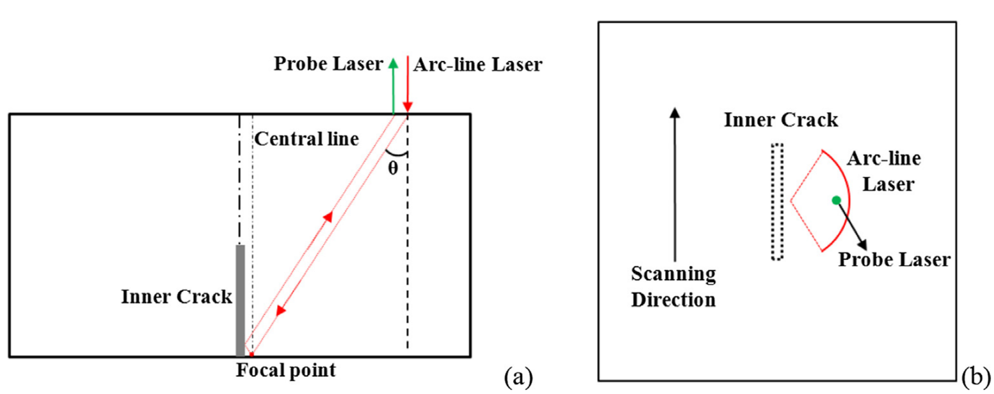

Fig. 2. Schematic diagram of inner crack inspection with arc-line laser: (a) cross-section view and (b) top view.