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Mid-infrared pulsed laser ultrasonic testing for carbon fiber reinforced plastics

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ABSTRACT

Laser ultrasonic testing (LUT) can realize contactless and instantaneous non-destructive testing, but its signal-to-noise ratio must be improved in order to measure carbon fiber reinforced plastics (CFRPs). We have developed a mid-infrared (mid-IR) laser source optimal for generating ultrasonic waves in CFRPs by using a wavelength conversion device based on an optical parametric oscillator. This paper reports a comparison of the ultrasonic generation behavior between the mid-IR laser and the Nd:YAG laser. The mid-IR laser generated a significantly larger ultrasonic amplitude in CFRP laminates than a conventional Nd:YAG laser. In addition, our study revealed that the surface epoxy matrix of CFRPs plays an important role in laser ultrasonic generation.

1. Introduction

Carbon fiber reinforced plastics (CFRPs) have been used extensively as structural materials for airplanes and automobiles because of their high specific strength and corrosion resistance. Their application in airplanes has recently expanded not only to secondary structural components (e.g., flaps, tailplanes, engine covers), but also to primary structural components such as the body and main wings. Since CFRP components must satisfy required standards to ensure safety and reliability, non-destructive testing (NDT) of these components is indispensable, both during manufacturing and in service.

Ultrasonic testing (UT) is the most common method used to detect defects in materials and to evaluate their dimensions with wave analyses. Piezo-electric transducers are usually used in this method to transmit and receive ultrasonic waves. Since the transducer needs to be in close contact with a sample by a medium (e.g., gel, oil, or water) and to be manually handled from point to point, for large products this can be time consuming and costly. Alternative ultrasonic inspection methods such as water immersion and water jet also have disadvantages in cost and time lengths [1].

Laser ultrasonic testing (LUT) can potentially overcome these problems. In this technique, a pulsed laser beam is used to generate ultrasonic waves on a material surface by rapid thermal expansion at a low incident power density (thermoelastic effect) or by vaporizing the surface material at a high incident power density (ablation) [2,3]. In addition, another laser beam coupled to an interferometer is used to detect the ultrasonic waves as they are transmitted through the material. Since LUT allows instantaneous and contactless inspection, it has many advantages [3]. While a number of studies and applications of LUT for metals have been widely reported, LUT applications for polymeric materials such as FRPs are still limited. One of the main reasons for this is the low signal-to-noise ratio (SNR) of LUT compared with conventional UT. In addition, polymeric materials are significantly attenuating materials.

Dubois and Drake revealed that a laser beam with a wavelength near 3.2 μm is optimal for ultrasonic generation in CFRPs [1,4]. This is because the absorption bands of the carbon-hydrogen stretching vibration and the oxygen-hydrogen stretching vibration in an epoxy matrix exist in this wavelength range, and because the moderately deep penetration depth of 50–100 μm in CFRPs yields efficient ultrasound generation. However, a laser with such a wavelength is not readily available. Therefore, commercial lasers, e.g., Nd:YAG lasers [5–8] or CO_2 lasers [4] have been used for LUT of CFRPs, some of which use transducers for detecting ultrasonic waves to improve the SNR [5,8].

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Thus, we have developed the most efficient wavelength conversion device for generating 3.2 μm wavelength, mid-infrared (mid-IR) pulsed light by pumping an optical parametric oscillator (OPO) using an Nd:YAG solid-state laser [9,10]. Since the wavelength conversion device and the solid-state laser are both compact and robust, our mid-IR pulsed laser is the most suitable source for laser ultrasonic generation in polymeric materials. Hence, we have developed an LUT system composed of an Nd:YAG laser, a wavelength conversion device, and a laser interferometer for detecting ultrasonic waves. It has been confirmed that this system can generate and receive ultrasonic waves in CFRPs, and was able to successfully detect delamination in CFRPs using a C-scan mode [9].

The purpose of the present study is to quantitatively investigate the performance of LUT by the mid-IR laser compared with a conventional laser (Nd:YAG laser) in terms of the laser energy density and the CFRP damage threshold. Furthermore, since it is expected that the CFRP surface significantly affects the generation of ultrasonic wave by the laser, the correlation between the surface epoxy content and the wave characteristics was studied. It was found that the SNR was further improved when the CFRP samples were coated by a thin epoxy resin. A finite element (FE) simulation of the laser ultrasonic generation and propagation in CFRP laminates showed good agreement with the experimental results and revealed the influence of the surface epoxy properties on the ultrasonic waves. Using this system, we demonstrated higher quality images of the defects in the CFRP samples.

2. Experimental

2.1. Mid-infrared laser ultrasonic testing system

As shown in Fig. 1, the mid-IR LUT system was composed of an Nd:YAG solid laser (Centurion Plus, Quantel), an OPO wavelength conversion device, a sample scanning XY stage, and a laser ultrasonic observation system (AIR-1550-TWM laser, OPTECH VENTURES LLC.). The Nd:YAG laser delivered 1.064 μm wavelength pulsed light with a maximum energy of 50 mJ, a pulse width of 12 ns, a beam divergence of 8 mrad, and a maximum repetition rate of 100 Hz. The pulse light was input into the wavelength conversion device from the right, as shown in Fig. 1.

The detailed mechanism of wavelength conversion using OPO has been previously reported [9]. A specially developed crystal, a periodically poled Mg doped stoichiometric lithium tantalate crystal (PPMgSLT), was placed between two plano–plano resonator mirrors in the device. The Nd:YAG laser pulse was input into the crystal as a pump and then two pulsed beams of different wavelengths, idler and signal waves, were output from the opposite side of the resonator. The respective wavelengths of the idler and signal waves are decided by the wavelength of the pump laser; the quasi phase matching (QPM) grating pitch of the crystal; and the refractive indices of PPMgSLT at pump, idler, and signal waves, which depend on the temperature [9–11]. In order to adjust the wavelength of the idler wave to 3.2 μm, the grating pitch was designed to be 30.9 μm and the temperature was kept at 40 °C. The lengths and apertures of the crystal were 35 mm and 4 mm × 4 mm, respectively. The output idler wave signal was separated from the pump and the signal waves by filters.

In our system, the mid-IR pulsed laser or the Nd:YAG pulsed laser was selected for the ultrasonic generation source by removing or replacing the mirror, labelled (A) in Fig. 1. The pulsed laser was directed to the surface of a sample on the XY stage. The energy density (fluence) of the pulsed laser is determined by the power, repetition rate, and beam area of the laser. While the repetition rate was fixed at 100 Hz, the output of the Nd:YAG solid-state laser was controlled to keep the fluence of the mid-IR laser almost the same as that of Nd:YAG laser. The power and beam area on the stage were precisely measured by a power meter and beam profilers (Pyrocam III for mid-IR laser and SP620U for Nd:YAG laser,

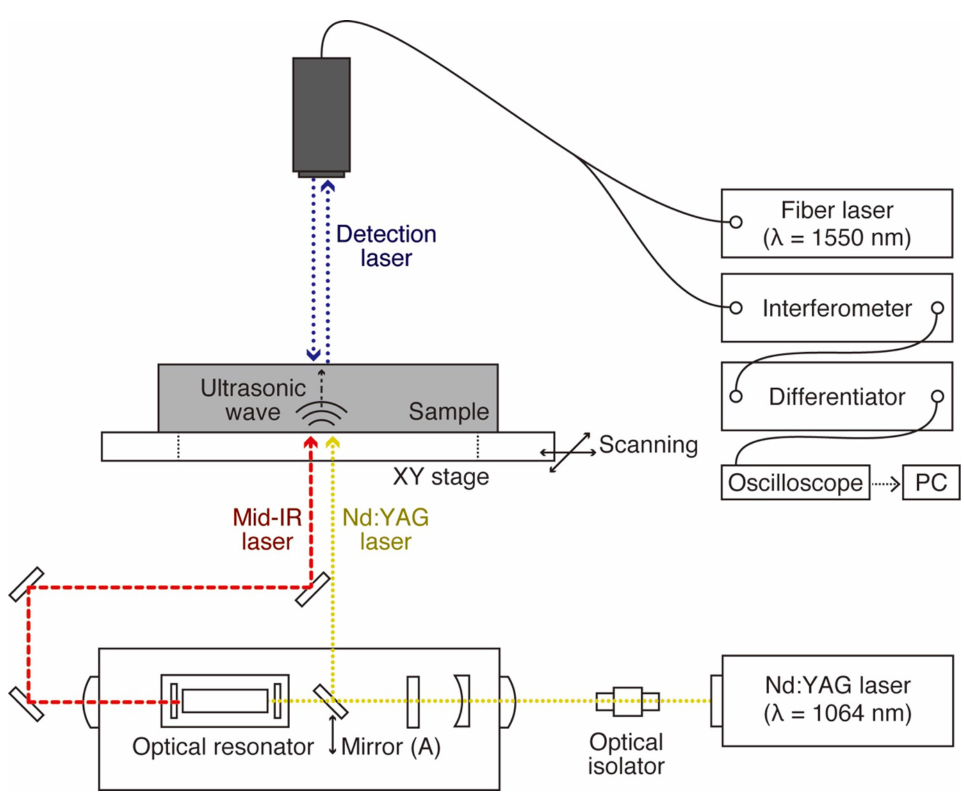

Fig. 1. The schematic diagram of the mid-IR laser ultrasonic testing system. The optical resonator converts the Nd:YAG laser to the mid-IR laser for the ultrasonic generation. The Nd:YAG laser was also used for the ultrasonic generation source by inserting the mirror (A).