Development of a highly-sensitive interferometer for laser ultrasonic testing of minute defects in metal materials

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ABSTRACT

Laser ultrasonic testing (LUT) is a noncontact and nondestructive method for inspecting internal and surface defects of materials. Ultrasonic waves are generated by pulsed lasers, reflected or scattered by defects, and detected by an optical interferometer through surface displacements. One of the most significant challenges of LUT is improving the sensitivity of the interferometer. In this paper, we report the development of a highly sensitive interferometer and its application in detecting minute defects within the internal structure and on the surface of metals. The interferometer utilizes a fiber-optic Sagnac configuration, which incorporates a loop of polarization-maintaining fiber components. We enhanced the sensitivity not only by amplifying the optical source power to increase the signal-to-shot-noise ratio, but also by eliminating stray light in the optical head to minimize beat noise. The resulting sensitivity, evaluated by noise-equivalent surface displacement, is 1.1×10^{-6} nm/$\sqrt{\text{Hz}}$, which is nearly half of the best sensitivity achieved by commercial industrial interferometers currently used for ultrasonic measurement. We successfully applied the interferometer to two specific cases: the detection of artificial line defects with a diameter of 100 μm engraved on the backside of a 10-mm-thick SS400 steel, and the detection of surface cracks with a width of 0.5 μm and depth of 10 μm. These results demonstrate the potential of our LUT system in detecting minute defects.

Keywords: Laser ultrasonic testing, noncontact, nondestructive, Sagnac interferometer

1. INTRODUCTION

Ultrasonic testing is one of the most mature methods in the field of nondestructive testing, and has been widely used to characterize material properties. Conventional ultrasonic testing utilizes contact transducers to transmit ultrasonic waves into materials and to receive the transmitted/reflected echoes. Liquid couplant (water, oil, etc.) is used to efficiently couple ultrasonic waves from the transducer to the material.

This method is not applicable for some cases where it is difficult or not allowed to contact the transducer to the material surface. One such situation is when the material has an extremely high temperature. Another example is when the material is so large that it is time-consuming and even painful to scan the wide area of the surface with the transducer and couplant.

An attractive alternative to the conventional ultrasonic testing is laser ultrasonic testing (LUT), where ultrasonic waves are generated and received by laser light in a noncontact and couplant-free way.[1] Over the past 60 years, LUT has developed from early research to commercialization across various areas of industry, including aerospace, automotive, and manufacturing. However, the LUT has fewer applications for testing materials onsite. One of the reasons is because optical ultrasonic detectors have a few orders of magnitude inferior sensitivity (minimum detectable signal) compared to that of contact transducers.

In this paper, a highly-sensitive interferometer for LUT and its successful application in detecting small defects in metals will be presented. After a brief explanation of a typical LUT system, a Sagnac interferometer will be introduced as an excellent candidate for an optical ultrasonic detector. Some options to improve the sensitivity are discussed. Its application in LUT for detecting artificial line defects and surface cracks will be demonstrated.

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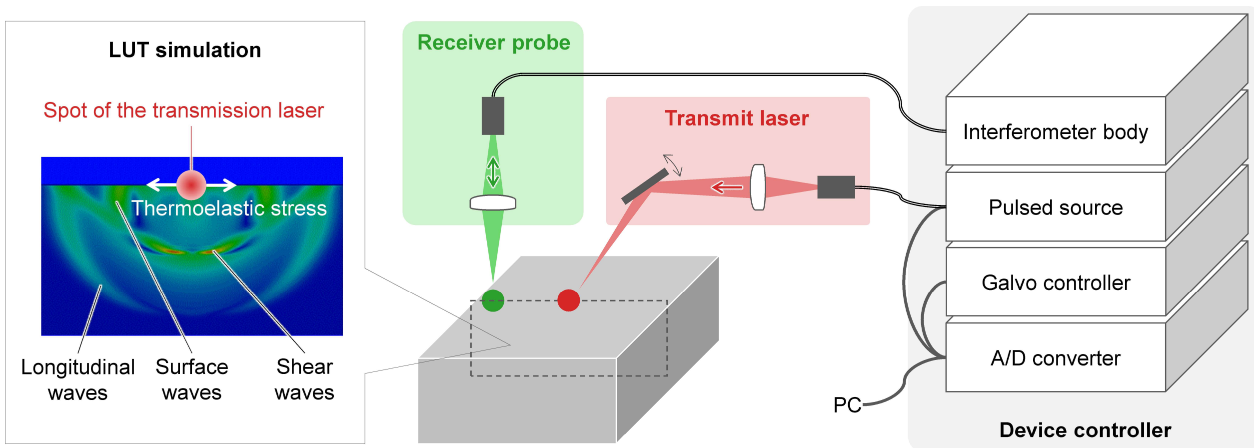

Figure 1. System schematic of laser ultrasonic testing.

2. OPERATION PRINCIPLE OF LASER ULTRASONIC TESTING

Figure 1 shows the operation principle of an all-optical LUT system. This system is composed of three parts: (1) a scanning pulsed laser source for ultrasonic generation, (2) an optical interferometer for ultrasonic detection, and (3) a device controller to synchronize the scanner and the acquisition system. The focused laser pulse is absorbed in the local area of a sample and causes heating, and the heating causes thermoelastic stress. This local stress becomes an epicenter of elastic ultrasonic waves. They propagate into the sample and get reflected or scattered by the internal structures, including defects. The backscattered wave causes surface displacement, which is then detected by the optical interferometer.

The bandwidth of the generated ultrasonic waves is determined by the pulse duration of the laser pulse. In a typical case, the pulse duration is on the order of nanoseconds, and the ultrasonic bandwidth is on the order of tens of megahertz.

Note that if the power of the generation laser is too high, the material may be melted or even ablated from the surface. Although this process generates strong ultrasonic waves, it is no longer nondestructive and therefore out of the scope of this paper. We assume that the generation laser causes only nondestructive thermoelastic processes.

3. OPTICAL INTERFEROMETRIC MEASUREMENT OF ULTRASONIC WAVES

3.1 Fiber Sagnac interferometer

Developing interferometers for ultrasonic detection is a key to enhance the overall performance of the LUT system. Quality of the interferometers can be judged by sensitivity, bandwidth, robustness against probe scanning, robustness against surface texture, and robustness against environmental changes (temperature, vibration, etc.).

Among various classes of interferometers (as shown in Fig. 2), an adapted form of the Sagnac interferometer has distinct advantages.[2,3] This system operates as a time-domain shearing interferometer, which reads temporal changes of axial surface position as fringes. Due to its common path nature, (1) the fringe contrast can be always near unity, (2) the effects of probe scanning, surface roughness, and environmental disturbance are all canceled out, and (3) a low-coherence source can be used to avoid excess interference between signal and stray light.

We developed a Sagnac interferometer with polarization-maintaining fiber-optic components shown in Fig. 3. A low-coherence radiation field from the superluminescent diode (SLD) source is split by a 50:50 directional coupler into two fields, one of which then undergoes an optical delay line. The optical paths of the two fields are combined at the polarizing beamsplitter (PBS) with mutually orthogonal linear polarizations. The two fields are focused on the surface of a sample through a quarter-wave plate (QWP) and an objective lens. The time of arrival of one field on the surface is time delayed relative to that of the other field. The reflected fields then travel back through the lens and QWP again. Since the polarizations of the two fields are exchanged through the roundtrip of the QWP, the field that initially transmitted through the PBS now gets reflected by the PBS, and vice versa for the other field. The time delay between the fields is canceled through the return paths and they interfere at the coupler. The output interfering fields, one of which is extracted by a circulator, are detected by a balanced detector. To obtain maximum phase sensitivity, a nonreciprocal phase shifter,[4] which introduces a phase

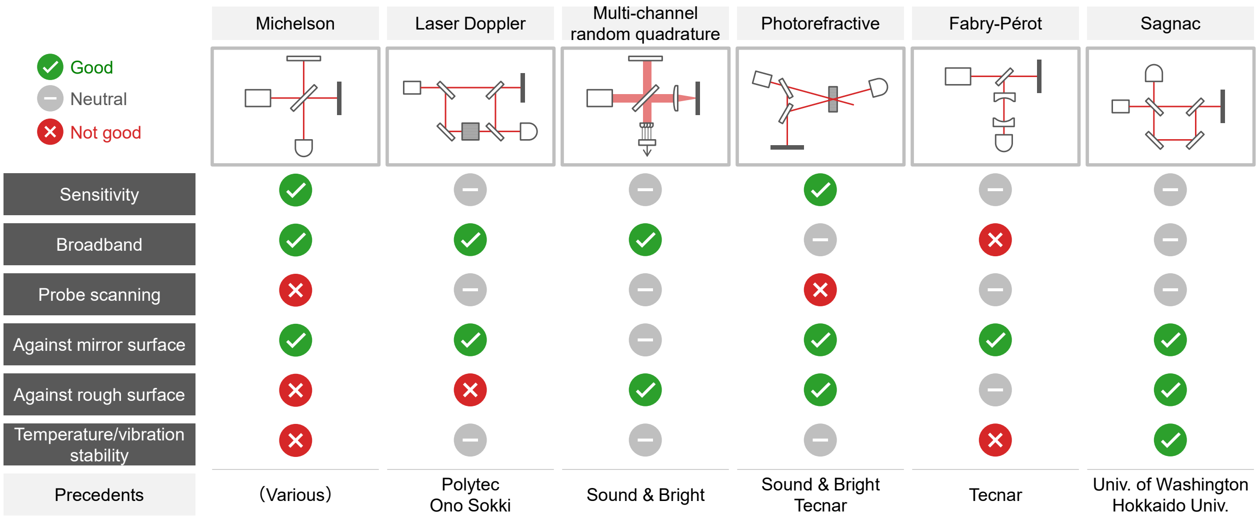

Figure 2. Candidates of interferometers for ultrasonic detection.

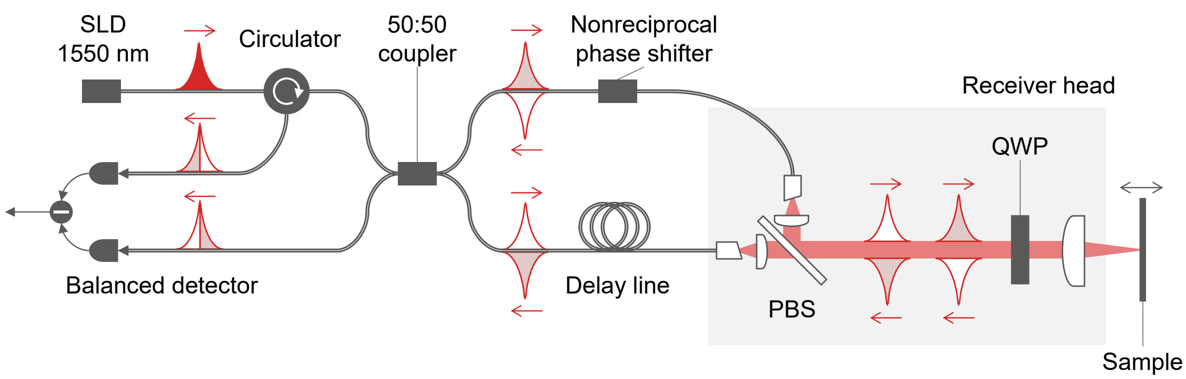

Figure 3. Schematic of the fiber Sagnac interferometer. The double lines indicate polarization-maintaining fibers between optical elements. SLD: superluminescent diode, PBS: polarizing beamsplitter, QWP: quarter-wave plate.

bias of $\pi/2$ between the two fields, is inserted between the coupler and PBS. The resulting signal current is approximately proportional to the time derivative of the surface displacement of the sample.

Figure 4 shows an example of ultrasonic waves detected by the Sagnac interferometer. Here the ultrasonic waves are generated by a transducer on the backside of a SS400 steel plate with a center frequency of 5 MHz. The transmitted wave and its reflections detected by the interferometer are displayed in parallel with those detected by the transducer. The pulse duration of the interferometer is obviously narrow in contrast with that of the transducer, indicating a wideband property of the interferometer to resolve minute structure of materials.

3.2 Improving the sensitivity

Enhancing the sensitivity of the interferometer is a major issue. The most common figure of merit for the sensitivity is noise-equivalent surface displacement (NESD). NESD of an interferometer is defined as a surface displacement where the signal-to-noise ratio (SNR) of the interferometer is equal to unity. A typical unit of NESD is displacement (e.g., pm) or displacement spectral density (e.g., $\mathrm{nm}/\sqrt{\mathrm{Hz}}$). To our knowledge, the smallest NESD among commercial interferometers for industrial ultrasonic measurement is about $2 \times 10^{-6}\ \mathrm{nm}/\sqrt{\mathrm{Hz}}$.[5]

To improve NESD, we need to increase the ratio of signal to the following kinds of noise:[6]

Shot noise Noise caused by the quantum nature of light. This is proportional to the optical power.

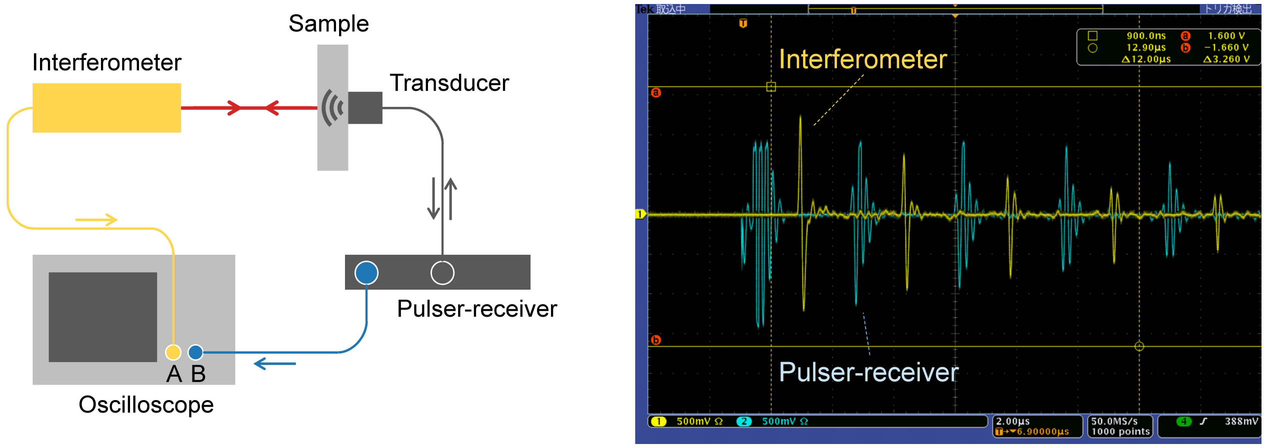

Figure 4. Optical detection of ultrasonic waves generated by a transducer.

Excess noise Noise as a result of the autocorrelation of the signal, due to beating between different spectral components within the linewidth. This noise is proportional to the squares of the optical power, and can be eliminated by balanced detection.

Beat noise Noise similar to the excess noise, but as a result of the cross correlation between signal and distant stray light. This noise is also proportional to the squares of the optical power. Note that this noise cannot be eliminated by balanced detection.

Dark noise Noise caused in electrical circuits of photodetectors and signal processors.

Increasing the optical power is a simple yet effective way to increase the SNR against the shot noise and dark noise. However, in the case of using a low-coherence light source, the excess noise and beat noise are the dominant factors which limit improvement of the SNR. While the excess noise can be reduced by the balanced detection, the beat noise still remains and becomes more problematic when the optical power increases.

The signal-to-beat-noise ratio decreases when distant stray light exists. In our case, the major source of stray light was the reflected/scattered light on the sample which travels back to the input fiber. Figure 5(a) shows one example of how stray light occurs in the receiver head, where a portion of the backward light unintendedly transmits through the PBS. This type of stray light is caused by polarization errors such as (1) insufficient polarization extinction ratio of the PBS, (2) retardance error of the QWP, and (3) perturbation of polarization on the sample or in the receiver head. The resulting beat noise was periodic in the frequency domain, as shown in Fig. 5(c)(i), where the stray light power level relative to the signal was −27 dB. The frequency-domain period of the noise corresponds to the inverse of the time delay between the signal and stray lights.[7]

We adopted an off-axis design for the receiver head to eliminate the stray light physically, as shown in Fig. 5(b). The specular reflected light from the sample does not couple to the input fiber regardless of the polarization errors listed above. Note that we still need to reduce the polarization errors since a fraction of the scattered light on the sample goes back to the input path. With a stray light level of −57 dB, the beat noise was drastically reduced as shown in Fig. 5(c)(ii).

In addition to eliminating the stray light, we amplified the optical source power to increase the amount of optical power on the detector to 15 mW, which is near the saturation limit of the detector. The measured NESD was about 1.1×10^{-6} nm/$\sqrt{\text{Hz}}$ at the optimum frequency of 10 MHz (Fig. 5(d)), which is nearly half of the best sensitivity achieved by commercial industrial interferometers. We can expect further improvement of NESD by amplifying the optical source power more while ensuring a higher saturation limit of the detector.

4. APPLICATION IN DETECTING SMALL DEFECTS OF METALS

We demonstrate application of the Sagnac interferometer in LUT for detecting minute defects of metal materials. Figure 6(a) shows the experimental setup. The overall system of LUT is based on a commercial LUT instrument (LUVI-ST4N, Tsukuba

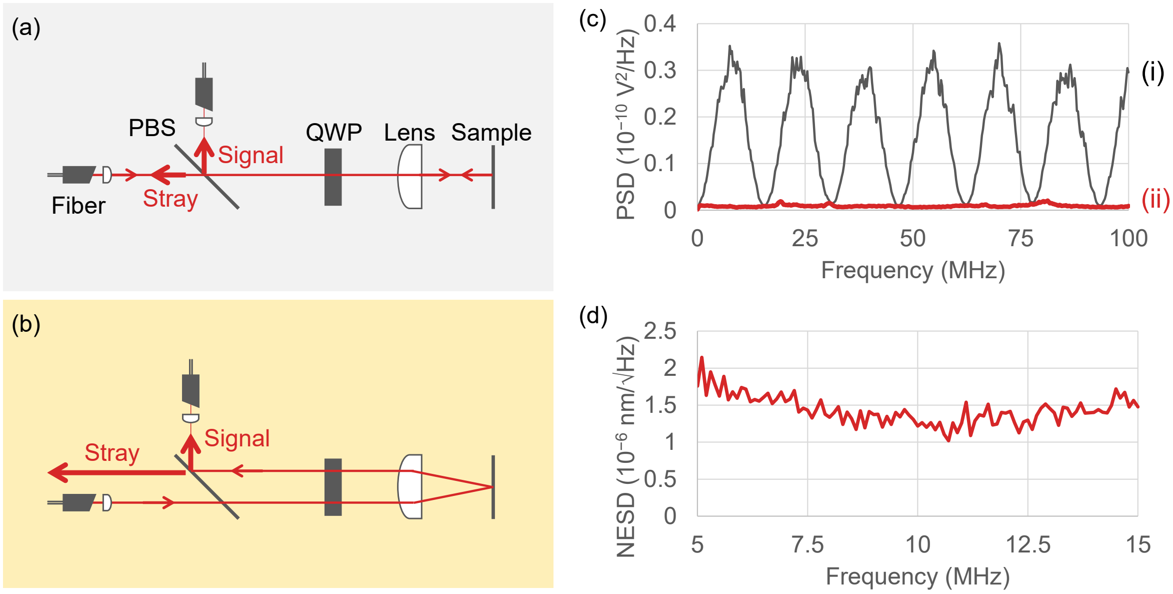

Figure 5. Schematic of eliminating stray light in the optical head to suppress beat noise. (a) An on-axis design of the receiver head where the stray light comes back to the input fiber, (b) an off-axis design for eliminating the stray light, (c) power spectral density of the detected noise voltages with (i) the on-axis design and (ii) the off-axis design. (d) measured NESD with the off-axis design, displayed as displacement spectral density.

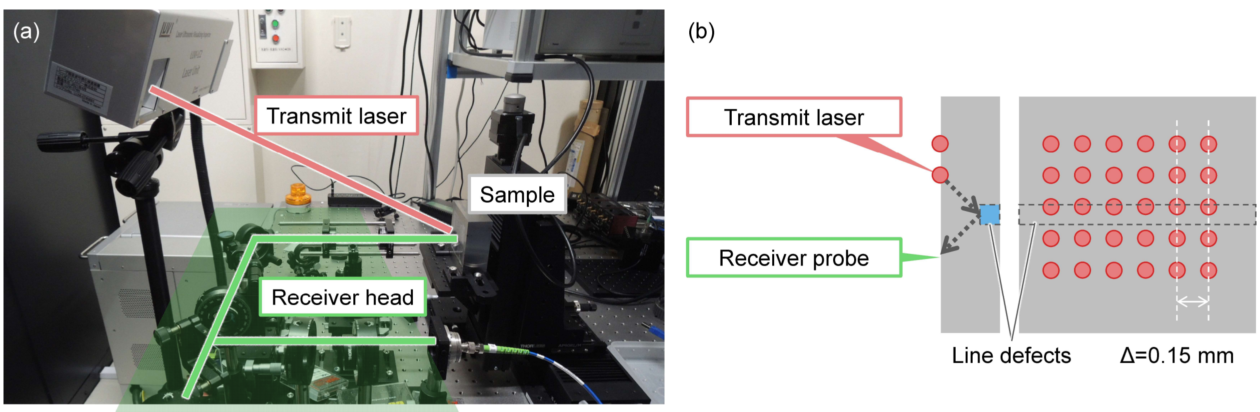

Figure 6. Experimental setup of the LUT system for detecting defects in metals. (a) Photo of the setup around the sample, (b) schematic of focused spots of the scanning transmit laser and the receiver probe.

Technology), which incorporates a transmit pulsed laser source with galvo scanners, an acquisition system of an external ultrasonic detector, and a software system for visualizing propagations of detected ultrasonic waves. The energy, repetition rate, and duration of the laser pulse are 2 mJ, 5 kHz, and 10.4 ns, respectively. The Sagnac interferometer is combined into the LUT system as the external detector. The measurement bandwidth is set to be 1–32 MHz, corresponding to a submillimeter ultrasonic wavelength in typical metal materials. Figure 6(b) shows a schematic of focused spots of the transmit laser and receiver probe on a sample. While the position of the receiver probe is fixed, the transmit laser is scanned on the sample in lattice form.

The first example is detection of artificial line defects engraved on the backside of a 10-mm-thick SS400 steel. The widths of the line defects are 100 μm, 80 μm, and 60 μm, respectively. Figure 7 shows the detected ultrasonic waves in B-scan images i.e., cross-sectional views along a scan axis. The average number of scans is set to be 36. We can see irregular echoes in the images, indicating echoes from the line defects. Since the dimensional scale of those defects is near the ultrasonic wavelength, our result shows that resolution of the LUT system reaches the diffraction limit of the ultrasonic

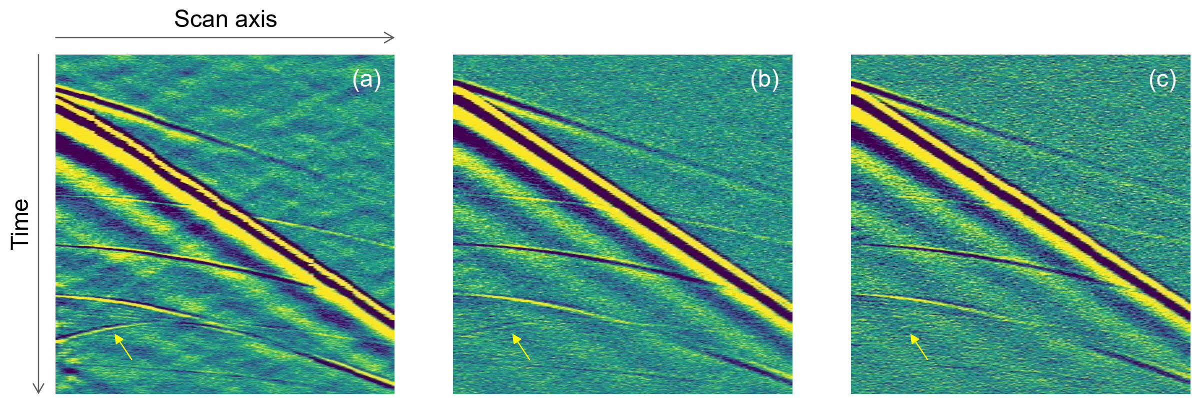

Figure 7. B-scan images of artificial line defects on the backside of 10-mm-thick SS400 plates. The widths of line defects are (a) 100 µm, (b) 80 µm, and (c) 60 µm, respectively. The arrows indicate the echoes from the line defects.

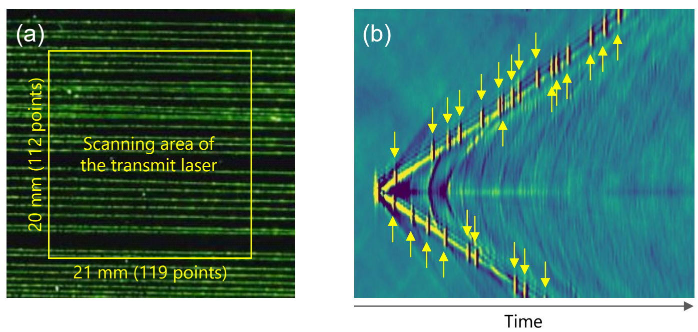

Figure 8. Demonstration of detecting surface cracks. (a) a fluorescent pattern of defects of the sample with indication of the scanning area of the transmit laser, (b) a B-scan image of the surface wave, where the arrows indicate scattering at the surface cracks.

waves.

Another example is detection of surface cracks in a nickel-chromium coating (Fig. 8). The sample is a standard test piece for fluorescent penetrant testing (JIMA PT TP-01). The dimension of the cross section of a crack is 0.5 µm × 10 µm. The scanning area of the transmit laser is about 20 mm square. Figure 8(b) shows a B-scan image of the surface wave, with the averaging number of 4. The arrows indicate scattering at the surface cracks. It is confirmed that the positions of scattering are all consistent with the fluorescent pattern of the defects (Fig. 8(a)). Due to the large amplitude of the surface waves, we can detect the cracks a few orders of magnitude smaller than the ultrasonic wavelength.

5. CONCLUSIONS AND FUTURE PROSPECTS

LUT is an excellent approach to inspect material properties in a noncontact way, and a key part is the interferometer for ultrasonic detection. We have developed a Sagnac interferometer for LUT and applied it in detecting small defects in metal materials. The sensitivity of the interferometer has been improved by eliminating stray light to suppress the effect of beat noise, as well as by amplifying the optical source power. Our LUT system has successfully resolved defects as small as the ultrasonic wavelength inside a metal material, and even smaller cracks on the surface of the sample. These results demonstrate the potential of our LUT system in detecting minute defects.

For industrial application, one major technical issue of the interferometer is to align the probe beam to be normal with the sample surfaces. Since the sample surfaces in industrial situations are often curved, the tilt of the probe beam should be controlled in real time to ensure that the specular reflection of the probe beam is collected by the receiver head. We are developing a prototype of the alignment system, shown in Fig. 9, where the beam tilt is compensated by a two-axis steering mirror positioned at the conjugate of the sample surface.

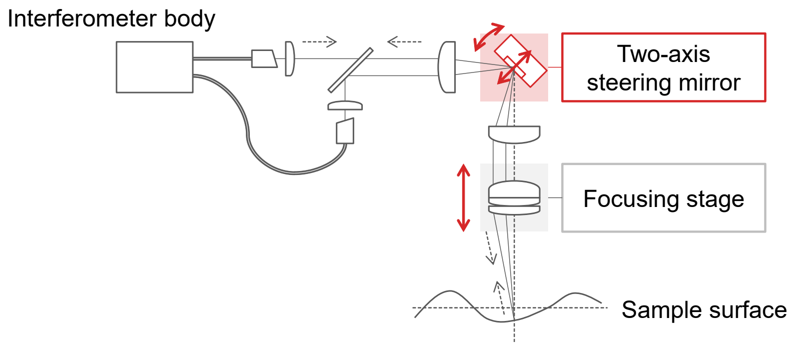

Figure 9. Prototype of our alignment system of the interferometer head.

Development of industrial application of LUT is now ongoing, including in situ inspection of welding processes.[8] For practical use, the transmit and receiver heads of the LUT system may be installed on a robot system, which allows us to inspect complex, large materials onsite.

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