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Detection of Fatigue Damage by Using Frequency Attenuation of a Laser Ultrasonic Longitudinal Wave

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1. Introduction

The measurement of fatigue damage in nuclear power plant components is very important to prevent a catastrophic accident and the subsequent severe losses. Specifically, it is preferred to detect at an early stage of the fatigue damage. If the fatigue damage that is in danger of growing into a fracture is accurately detected, an appropriate treatment could be carried out to improve the condition. Although most engineers and designers take precautions against fatigue, some breakdowns of nuclear power plant components still occur due to fatigue damage. It is considered that ultrasound testing technique is the most promising method to detect the fatigue damage in many nondestructive testing methods. Ultrasound testing method has a variety of elastic waves, such as a longitudinal wave, a shear wave, a surface wave and a lamb wave. Also we can use various analysis methods, such as a velocity variation and a signal attenuation.

Laser ultrasonic testing has attracted attention as a non-contact testing technique. This system consists of a pulse laser to remotely generate ultrasound and a laser interferometer to remotely measure the surface displacement due to the generated ultrasound. This non-contact testing technique has the following advantages over the conventional piezoelectric transducers. Firstly, the inspection system can be remotely operated for a structure in hostile environments, such as in high radioactivity, high temperatures and narrow spaces. Secondly, we can obtain lots of information from the received ultrasonic waveforms because the laser ultrasonic technique does not require fluid couplant which disturbs the ultrasonic waveforms. Thirdly, laser ultrasound has a wideband spectrum and a high spatial resolution. Therefore, the laser ultrasound provides more accurate information for a testing material and has potential for the detection of fatigue damage in various metals composing a nuclear power plant[1, 2].

In this paper, we have investigated the detection of fatigue damage in SUS316 by using the frequency attenuation of a laser ultrasound. We configured a laser ultrasonic inspection system which consists of a pulse laser and a Confocal Fabry Perot interferometer(CFPI) with a CW laser beam for the detection experiments. We extracted the information of fatigue damage by using the normalized frequency attenuation of a laser ultrasonic longitudinal wave according to the rate of fatigue damage. Here, we report on the experimental results of the frequency variations and the specific frequency attenuation against the propagation distance according to the rate of fatigue damage.

2. Experiments for the detection of fatigue damage using a laser ultrasonic inspection system

We used a laser ultrasonic inspection system to detect the fatigue damage of a sample of SUS316. The used laser ultrasonic inspection system consists of a personal computer with a high-speed data acquisition board(AL81G, ALI), a pulse laser (Quantel-Brilliant) and a CFPI(CFT-500, Buleigh, FSR 150MHz) with a stabilized CW green laser which has already been reported[3]. Six specimens, fatigue rates of 30%, 50%, 70%, 80%, 90% and 99% of a fracture cycle N_f, are prepared for experiments. We used multiple reflected longitudinal waves of a laser ultrasound as shown in Fig. 1.

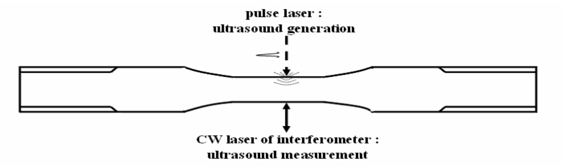
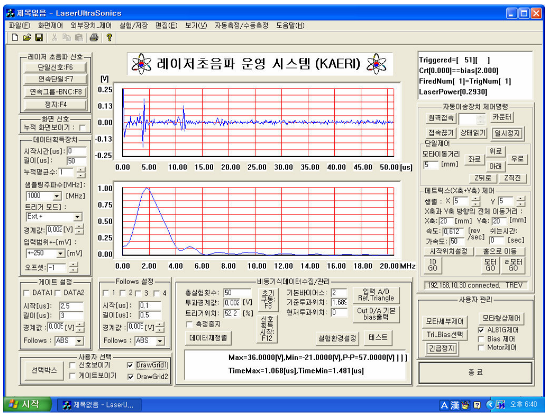


Fig. 1 Experimental setup for detection of fatigue damage in SUS316.



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경계값: 0,002 [V]
입력범위+-[mV] : +-250 [mV]
오프셋: -1

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길이[us]: 3
경계값 : 0,005 [V]
Follows : ABS

☐ 1 ☐ 2 ☐ 3 ☐ 4
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길이[us]: 0,5
경계값 : 0,005 [V]
Follows : ABS

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기준투과위치: 1,68
현재투과위치: 0

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TimeMax=1.068[us],TimeMin=1.481[us]

☐ 신호보이기 ☑ DrawGrid1
☐ 게이트보이기 ☑ DrawGrid2

모타이동거리 5 [mm]
행렬 : X 5 Y 5
X축과 Y축 방향의 전체 이동거리 :
X축: 20 [mm] Y축: 20 [mm]
속도: 0,612 [rev/sec] 쉬는시간: 0 [sec]
가속도: 50
192,168,10,30 connected, TREV

☑ AL81G제어
☐ Bias 제어
☐ Motor제어

Fig. 2 Configuration of the main control software for a laser ultrasonic inspection system.

The specimen surface was irradiated by a circle-shaped pulse laser beam whose diameter was about 5 mm. A train of longitudinal wave echoes is observed as shown in the main control software display of Fig. 2. Here, the center-upper graph is a captured ultrasonic wave in the time domain and the center-lower graph is a spectrum signal in the frequency domain. These signals can be displayed in real time on the monitor.

The measured longitudinal waves for the fatigue damaged samples of 0% and 70% are shown in Fig. 3. The first signal that appears at about 3.9us is the first longitudinal wave. The subsequent echoes were observed until the 4th longitudinal wave with a constant interval which corresponded to the round trip time. We can observe in Fig. 3 that the cycle period of the laser ultrasonic signal is slightly extended in proportion to the fatigue damage rate.

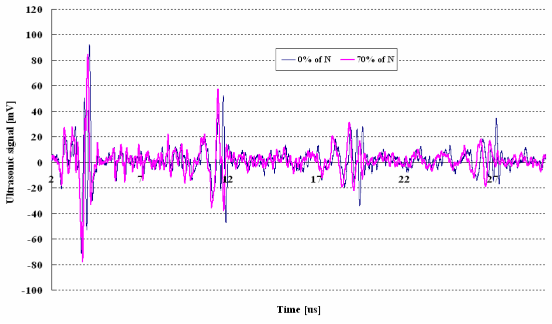

Fig. 3 Measured ultrasonic waveforms at the 0% and 70% of fracture cycle N_f.

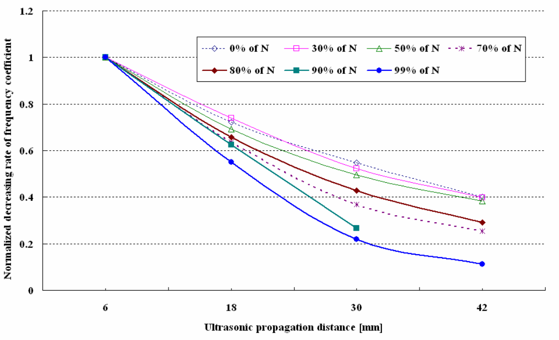

Fig. 4 Normalized frequency attenuation against the propagation distance for each fatigue damaged sample.

The frequency component at 1.94MHz in the ultrasonic signals is calculated by Fourier transformation. The normalized frequency attenuation is plotted against the ultrasonic propagation distance as shown in Fig. 4. The vertical scale is the normalized frequency amplitude by F_i/F_1. Here F_1 is frequency amplitude of 1.94MHz for the first captured longitudinal wave and F_i is the frequency amplitude for the (i-1)th echoed longitudinal wave. Here, we can see that the ultrasound attenuation increases when the fatigue damage is increased.

The 4th frequency amplitude for the fatigue damaged specimen of 90% is not displayed because we can not extract the 4th echoed longitudinal wave from the captured signal because of the low signal-to-noise ratio. We can discriminate the fatigue damage from over the 70% of fracture in this experiment.

It is not easy to establish a valid reason why the frequency attenuation increases with increasing rate of fatigue damages. However, one reason would be because of the generation of the dislocation at grain boundaries and also, the subsequent growth of micro-cracks.

As for the experimental results, we can more clearly discriminate the rate of fatigue damage when the propagation distance is longer. In this experiment, the discrimination efficiency is the best at the propagation distance of 30mm. The discrimination efficiency at the propagation distance of 40mm is slightly lower because of the low signal-to-noise ratio when compared to the distance of 30mm.

3. Conclusions

We have built a laser ultrasonic inspection system which consists of a pulse laser and a CFPI with a CW laser to remotely detect the fatigue damage in SUS316. Specimens are prepared to seven stages according to the fatigue loading cycles. We have observed that the normalized frequency attenuation ratio of the laser ultrasonic longitudinal wave against the propagation distance increases in proportion to the ratio of fatigue damage. Thus, the laser ultrasonic technique provides not only the non-contact inspection but also valuable frequency component information. Therefore, the evolution of laser ultrasonic inspection technique has the potential for the detection method of fatigue damage in nuclear power plant components.

For further research, it is necessary to develop efficient signal processing techniques for the frequency domain because a frequency component is sensitive to noises. Also, we need to improve the signal-to-noise ratio of the laser ultrasound for an improvement of the detection efficiency.

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