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Laser-induced surface acoustic waves and their detection via diagnostic systems for detecting radiation damage on steel materials of nuclear devices

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ABSTRACT

The development of a non-destructive, non-contact diagnostic system to detect radiation damage is very important for measuring radioactive materials. A system using surface acoustic waves (SAWs) induced and detected by lasers was developed. The propagation velocities of SAWs on stainless steel irradiated by 20 keV He and Ar ions were investigated, and a tendency for the velocity to increase with an increase in ion irradiation was observed. This tendency may be due to surface modification. A non-linear effect on ion irradiation versus normal surface velocity in the vertical direction was confirmed.

1. Introduction

Non-destructive, non-contact diagnostic methods for nuclear materials are crucial to avoid radioactive contamination. Non-destructive methods are beneficial in that they do not disturb the specimen regardless of the physical distance of the measurement. Non-contact methods ensure that the specimen continues functioning throughout the measurement process. For a diagnostic system to evaluate mechanical properties of material surfaces, surface acoustic waves (SAWs) are an ideal non-contact method. SAWs, are also known as Rayleigh waves, propagate at about 0.92 the velocity of transverse wave. SAWs propagate about one wavelength near the surface of the medium [1]. In recent years, due to advances in thin-film technology, SAWs have been used in electrical devices such as frequency filters and optical elements [2]. Several optical methods are contributed to detect SAWs. Changes in reflection angles owing to the displacement of the laser spotted surface by SAWs [3] and Doppler shift of the reflected laser [4]. For SAW excitation, an ultrasonic testing (UT) transducer with a wedge adapter is generally used for narrow-band excitation. The transducer should be in contact with the specimen to convey the ultrasonic wave, but it would not be a non-contact method. A pulsed laser excitation is not so stable but it can be done without physical contact. Therefore the method of detecting pulsed laser excited SAWs via laser reflection by the surface makes it possible to observe the physical properties of the near-surface region where SAWs propagate in an almost non-destructive and non-contact way. It may be possible to observe inner material stress from the non-linearity of the signal intensity and the excitation power, intensity elastic constant of the medium from the delay time of the excitation and detection, and the presence of defects from discontinuity. In this paper, we report the development of a SAW diagnostic system that uses the laser-Doppler effect and evaluate the system via steel materials for nuclear devices modified by ion irradiation.

2. Laser Doppler detection of laser induced SAWs

2.1. Excitation of SAWs induced via pulsed laser

When a laser beam irradiates a solid surface, acoustic waves are generated and their propagation can be described by thermal diffusion and elastic equations. For a solid, isotropic, perfectly elastic half-space, from the boundary conditions, the propagation velocity of SAWs, v_{SAW} which propagates near the surface is described with the velocity of transverse wave v_s and Poisson's moduli σ, and can be written in the form

$$v_{SAW} = v_s(0.87 + 1.12\sigma)/(1 + \sigma) \quad (1)$$

Here, Poisson's moduli σ varies from $0 < \sigma < 0.5$, and $v_{SAW} \sim 0.9v_s$.

SAWs have two inhomogeneous waves in the longitudinal and transverse direction. SAWs propagate along the surface. Therefore,

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a rectangular line beam spot on the surface excites SAWs that propagate almost one-dimensionally along the surface. The SAWs which propagate in one-dimension have in principle no energy loss, and can propagate infinitely.

2.2. Detection of SAWs

The experimental set-up used in this study was completely updated from our former set-up described in Ref. [4]. The SAWs were detected in a non-contact environment by using an optical heterodyne method with a laser Doppler vibrometer (Denshi-Giken Vibroducer V1002 [5]) shown in Fig. 1, that uses Doppler-shift. The incident laser is He–Ne (wavelength λ=632.8 nm) 1 mW, and the beam diameters are less than 20 μm. The laser beam was modulated with f_a~80 MHz by an acoustic optical module (AOM). The differences of signal intensity between the incident beam and the reflected beam from a target object are observed. The normal vibration velocity, v in the direction vertical to the reflection surface can be obtained by the differential of the visibility, f_d

$$v = f_d \lambda / 2 \tag{2}$$

2.3. SAW diagnostic system

The SAW diagnostic system configuration used in this experiment conducted at JAEA, Tokai, is shown in Fig. 2. The pulsed laser was Nd:YAG, having a 532 nm wavelength, maximum pulse power of 100 mJ, a pulse duration of 4 ns, and a frequency of 1–15 Hz. The reason that the second harmonic wave of Nd:YAG was used is the advantage in visibility for delicate focusing. The laser beam was focused by a cylindrical lens, and the spot size was a rectangular line of about 10 mm × 0.1 mm. The power density was controlled by about 10^{12} W/cm^2 in which laser ablation caused damage to the surface.

The generated pulse was a trigger to time the signal detection. The SAW propagation distance from the pulsed laser line to the detection spot was scanned from 0 mm to 20 mm by shifting the laser Doppler vibrometer head. The detection laser irradiates vertically so the surface encounters the incident and reflects light to the same optics. A high-zoom camera was used to observe the measured area.

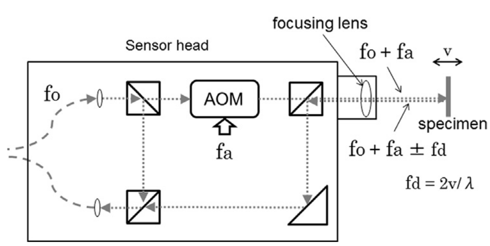

Fig. 1. Schematic view of the laser Doppler vibrometer.

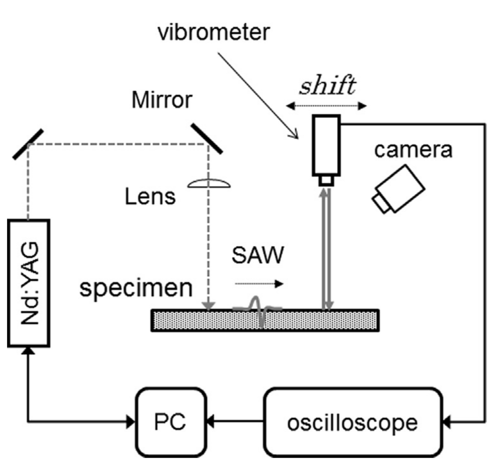

Fig. 2. SAW diagnostic system.

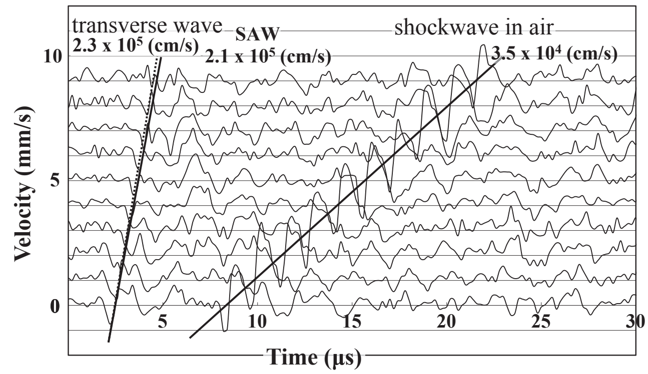

Fig. 3. Detected waveforms on Cu surface.

3. Results

3.1. Detection of SAWs

A pulse laser irradiation onto a specimen surface generates various waves. The component of vibrations in vertical to the surface can be detected by the laser Doppler vibrometer. Optical noises due to stray light and electrical noises due to electric triggers can be removed easily owing to the correlation of the distance between the excitation line and detection spot. The waveforms detected by the diagnostic system are shown in Fig. 3. The horizontal axis is time in microseconds, and the vertical axis is normal surface velocity in the vertical direction towards laser detection in mm/s. The upper waveform is 0.5 mm further from the laser excitation point to the detection point than the lower one. The irradiated laser pulses produce SAWs, various modes of bulk waves (transverse wave, longitudinal wave) and air shock waves on the specimen surface. SAWs exhibit approximately the same waveform for each pulse. Bulk waves exhibit different waveforms for each pulse, which can be isolated from SAWs by averaging 64-accumulations. Further, the waveform of the shock wave due to the air can be separated, because the speed of sound in air (3.5 × 10^2 m/s) is sufficiently slower than that of SAW.

3.2. Ion irradiation onto metal surfaces

The nuclear steel material specimens were irradiated using an RF ion source at JAEA, Takasaki. The rectangular specimens (20 × 5 × 1 mm^3) of HCM12, SUS304, and SUS316FR (normal, LB low boron and HB high boron) were irradiated in a 10^{-5} Pa vacuum at room temperature. The surfaces were polished with 0.3 μm buffs or provided nanopolish of 10 nm smoothness. The specimens were selected to evaluate a possible candidate for materials in fast breeder reactors. The details of the specimens are described in Ref. [6]. The irradiated ions were 20 keV He with 10^{17} and 10^{18} doses and 20 keV Ar with 10^{17} doses. The projected ranges in the target specimens were estimated by SRIM (stopping and range of ions in matter) [7] and are summarized in Table 1.

3.3. Propagation velocities of SAWs

The amplitudes of the SAWs excited by pulsed laser are not constant because the surface conditions of the interaction spot are not the same for each laser shot. The propagation velocity of SAWs

Table 1
Calculated projected ranges in target specimens [7].

	He 20 keV	Ar 20 keV
Ferrite; HCM12A	78.8 nm	10.6 nm
Austenite; SUS304, SUS316FR(normal, LB, HB)	78.0 nm	10.5 nm
Cu	79.8 nm	9.9 nm

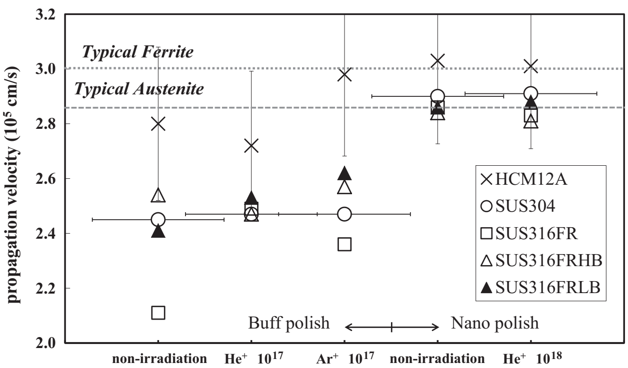

Fig. 4. Propagation velocities of SAWs on specimens. The left 3 groups have buff-polished surfaces, and the right 2 groups have nano-polished surfaces. The values for ferrite (2.9×10^5–3.1×10^5 cm/s) and austenite (2.85×10^5 cm/s) are shown for reference.

on homogeneous plane surface is characterized by the material. The velocity is very delicate by the surface conditions.

The observed propagation velocities of SAWs on the specimens are shown in Fig. 4. The propagate velocities were calculated from the correlation of time as shown in Fig. 3, and the accuracy is off by error less than 10 percent which is not shown in the figure. Error bars of 10% were added for reference for the data of HCM12A only. There are also uncertain factors originating from surface conditions, such as microdamage, erosion, and deposition. The left 3 groups used buff-polished surfaces and the right 2 groups used nano-polished surfaces.

In this experiment, the pulse length of the Nd:YAG laser is about 4 ns, which corresponds to 12 μm SAW wavelength on the 3×10^5 cm/s SAW propagation velocity specimens. However, excite phenomena from pulsed lasers have numerous microscopic events [8]; therefore waveforms of SAW excited from a pulsed laser are piles of waves whose wavelengths are much shorter than 12 μm.

The propagation of SAW depends greatly on the surface conditions, and there is an obvious difference in the non-irradiation cases. For nano-polished surfaces, the velocities are nearly consistent with typical values for ferrite (2.9×10^5–3.1×10^5 cm/s) and austenite (2.85×10^5 cm/s). On the other hand, the velocities of buff-polished surfaces showed lower values. In cases where surfaces were buff-polished, there is a tendency for the propagation velocity of SAWs to increase after being irradiated. This can be explained as surface smoothing by irradiation. Ion irradiation can also increase the shear modulus near the surface. The difference in ions such as helium or argon shows the tendency of surface modified conditions. The projected range of argon is about eight times shorter than that of helium; therefore argon caused more damage than helium near the surface. In nano-polished surfaces, there were no significant changes. This can be explained that either the surfaces were too flat to be smoothed, or the smoothness of the surface prevented irradiation damages near the surface.

3.4. *Detection of non-linear effect*

The non-linear response of the laser power for excitation versus the SAW vibration on ferrite HCM12A specimens with

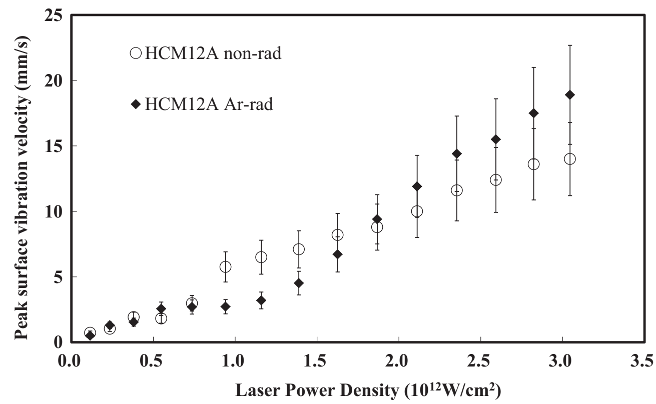

Fig. 5. Non-linear response of the laser power density for excitation by the SAWs normal vibration velocity on the ferrite HCM12A specimens with and without irradiation.

and without irradiation is shown in Fig. 5. The horizontal axis is laser power density, and the vertical axis represents the peak surface vibration velocity in the normal direction. In this Doppler detection system, the directly measured peak values of the vibrations are proportional to the amplitude. In the curve of non-irradiated specimens, the nonlinear effect was not significant and appeared at 1.4×10^{12} W/cm^2, however it did appear in the irradiated specimens. It is considered that the response characteristics of SAWs were changed by ion irradiation. The transient process of how the energy from the excitation laser is converted into SAW is complicated. The proportion of the laser absorption on the surface is depending on the surface conditions [4]. The non-linear effect that appears in the response characteristics of the material by ion irradiation shows that a decrease in breaking strength near the surface could be measured non-destructively.

4. Conclusion

We prepared a non-destructive and non-contact inspection system by laser pulse excitation and laser Doppler observation of SAW. The system is suitable for observing activated nuclear materials with less radioactivity diffusion. To evaluate the correlation between SAW response characteristics and radiation damage, changes in SAW responses of ion-irradiated specimens were confirmed. After specimens were irradiated at JAEA, Takasaki, a function test of the SAW diagnostic system was conducted at JAEA, Tokai. The results of the propagation velocities of SAWs have potential to evaluate surface modifications. The non-linear response system is a candidate for a non-destructive diagnostic method.

Acknowledgments

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