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Evaluation of annealing and double ion beam irradiation by a laser-induced and laser-detected surface acoustic wave diagnostic system

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HIGHLIGHTS

- We modified the surface of specimens by heat treatment and double ion beam irradiation.
- The diagnostic was performed by observation of SAWs.
- A non-linear nature of SAWs indicates changes in the mechanical properties.
- The potential of the SAWs diagnostic system was demonstrated.

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ABSTRACT

The effects of annealing and double ion irradiation on nuclear structural materials were investigated using a novel, non-destructive, non-contact diagnostic method. A laser-induced and laser-detected surface acoustic wave (SAW) was adopted as a diagnostic system. The SAWs propagation velocity and the SAWs vibration velocity along the normal direction of the surface were measured to investigate mechanical properties of the substrates. Change of the shear modulus was detected in the annealed substrates. Non-linear effect on amplitude of the excited SAW was observed on the double ion irradiated materials. The potential of the SAW diagnostic system for assessing nuclear structural materials was demonstrated.

1. Introduction

Non-destructive, non-contact diagnostic methods for assessing the character of nuclear materials are desirable in order to avoid radioactive contamination. A laser which is non-destructive and can be applied remotely may be especially well-suited for use in diagnostics because of its coherence and high power. Surface acoustic waves (SAWs), also known as Rayleigh waves, propagate on the surface of solid materials (Viktorov, 1967). Recently, SAWs are widely utilized for electrical devices, such as band path filters and touch panels. The researches on laser-excited SAWs have been conducted by various scientists and engineers (Kolomenskii and Schuessler, 2001). In our previous research, the effects for SAWs by ion irradiations on surfaces of carbon thin films (Kitazawa et al., 2003) and metal materials (Kitazawa et al., 2015) have been reported.

Properties of SAWs are well known (Viktorov, 1967). The propagation of SAWs on a semi-infinite isotropic material is described as a vector and second order tensor. In this study, the SAWs propagate only one direction along the surface; therefore measuring propagation is simply a matter of comparing the propagation velocity to the normal vibration velocity. The SAWs propagation velocity V_r is given approximately by the following Eq. (1).

$$V_r=0.92V_s=0.92\sqrt{G/\rho} \quad (1)$$

Here, V_s is the speed of the bulk wave (shear wave), G is the shear modulus and ρ is the density of the medium. The typical theoretical values on ferrite steels and austenitic stainless steels are; Vs ferrite $=2.9$–3.1×10^5 cm/s, V_s austenite $=2.85\times10^5$ cm/s. Here, supplemental factors, such as, temperatures and crystal directions are not taken into account. The vibration velocity in the normal direction of SAWs increases linearly as the excited laser power density increases (Kitazawa et al., 2015).

Stainless steel structural materials for the use in a fast breeder reactor (FBR) should be designed to endure up to 60 years in Japan.

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It should endure in the harsh environments of nuclear plants with constant exposure to radiation near the reactor core without any replacement during the design lifetime. High-chromium martensitic steels and austenitic stainless steels are used for FBR structural materials. It is therefore important to evaluate the damage due to neutron irradiation over the lifetime of the FBR plant. The irradiation of structural materials in the FBR plant is assumed up to 1 dpa and 30 ppm at an operating temperature of 828 K (Hasegawa et al., 2010). Here, dpa (=displacements per atom in the solid) is a unit for assessing displacement damage in the alloy (Teller, 1981). The SAW diagnostic system in this study is a novel method which has advantages for measuring highly radioactive specimens. Before measuring actual materials that are irradiated in a nuclear reactor, it is important to measure the specimen prepared by ion irradiation by an accelerator.

In this study, austenitic stainless steel and ferrite steel, as candidate structural materials for long life FBRs, were evaluated in terms of their response characteristics on SAWs, which may be sensitive to the generation of micro helium bubbles. Specimens were prepared by annealing and double ion beam irradiation to simulate irradiation in the FBR. Double ion beam irradiation is suitable for testing irradiation damage on He-related reactions because the ratio of helium content to dpa level can be changed without altering other parameters. Double ion beam irradiation was performed at the High Fluence Irradiation Facility (HIT) of the University of Tokyo at Tokai. Annealing is expected to affect whole of the material. The effects of irradiation by HIT are not confined to the surface since high energy ions are influenced to sufficient depth of the material.

2. Experimental

2.1. Laser-induced and laser-detected SAW diagnostic system

A laser-induced and laser-detected SAW diagnostic system is a non-destructive diagnostic for detecting radiation damage (Kitazawa et al., 2003; Kitazawa et al., 2015). In addition to conventional measurements, to perform a measurement of radioactive samples due to ion or neutron radiation, exposure of the measuring device is designed to be minimal. The system was improved from previous works by adding remote control, optical alignment and data processing system. The schematic diagram of the laser-induced and laser-detected SAW diagnostic system is shown in Fig. 1.

In the system, the SAWs were excited on the surface of specimen by irradiation of second harmonic wave of pulsed YAG laser (532 nm, 4 ns). The SAWs were detected by a laser Doppler vibrometer (Denshi-Giken Vibroducer V1002) using optical heterodyne method. The resolution was improved from the previous work by an additional signal processing unit (Denshi-Giken V0307), and then it was 10^{-12} m in displacement, 10^{-7} m/s in velocity and 10^{-7} m/s^2 in acceleration (Denshi-Giken, 2007). The laser beam spot on the surface was ellipse of 10 mm × 0.1 mm; in which the generated SAWs propagate in the nearly one-dimension along the short axis direction. The power density was about 10^{12} W/cm^2, which is lower than the threshold to cause laser ablation. The spatial resolution on the propagation direction is 0.1 mm, which corresponds to the laser beam width. The time resolution is 0.3 μs owing to the system, and then the minimum value of detectable displacement is approximately 0.1 μm. The SAWs propagation velocity was calculated by the correlation between the propagation distance and the response time. It was performed as fixing the SAWs excite line and horizontally sweeping the point of focus on the measurement sample in the propagation direction of the excited SAWs.

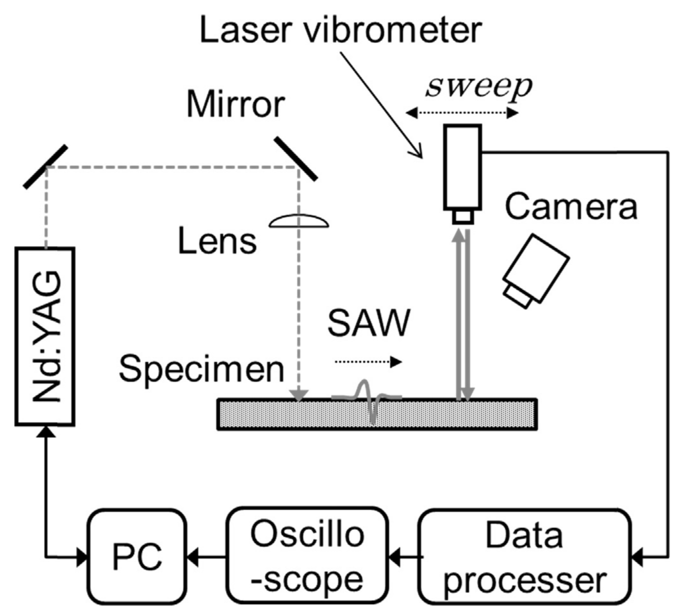

Fig. 1. Non-destructive, non-contact diagnostic system by laser-induced and laser-detected SAWs.

In addition to the SAWs, bulk waves, shock waves and stray lights were detected as signals. The bulk waves are isotropic and those average values of the velocity in the normal direction of the surface exhibit zero for multi pulses; therefore they can be separated from the SAWs which retain almost the same waveform for each pulse, by taking the average value from multi acquisition. The averaging was done in 64-accumulation, which appears to be suitable because more accumulation increases the risk of sudden noise. The shock wave of air propagates at the speed of sound (3.5×10^2 m/s) and it is sufficiently slow to be separated from the SAWs.

The surfaces of stainless steel samples were prepared through mechanical and electrolytic polishing to a roughness at the nanometer level. Previous experiments indicate that a surface roughness at a nano-meter level is necessary for a high accuracy measurement on SAW (Kitazawa et al., 2015).

2.2. Annealing

During irradiation in an assumed FBR, the materials will be heated to about 823 K (Nagae et al., 2011). For that reason, in order to separate the thermal effects on the material from the irradiation effects, we implemented annealing simulating the heat history of the temperature and time for materials in the FBR. The annealing was done in electric furnaces of six lots in air. In each lot, five pieces of materials were piled up. The temperature was controlled at 773, 823 and 873 K, and the duration of heating was 1000 and 2000 h.

The specimens were five materials, SUS304, SUS316FR, SUS316FRLB, SUS316FRHL and HCM12A. HCM12A is a high-chromium martensitic steel, and the others are austenite steel. The details of the specimens have been described elsewhere (Hasegawa et al., 2010). Their chemical composition is summarized in Table 1.

2.3. Double ion beam irradiation

Double ion beam irradiation was performed at HIT. Helium ions were ejected from the 3.75 MV Van de Graaff accelerator, and nickel ions were ejected from the 1 MV Tandem accelerator. The both ions were irradiated onto the target simultaneously. A foil