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Evaluation of irradiation embrittlement in RPV steels by EMAR measurements
電磁超音波共鳴法による圧力容器鋼の照射脆化評価

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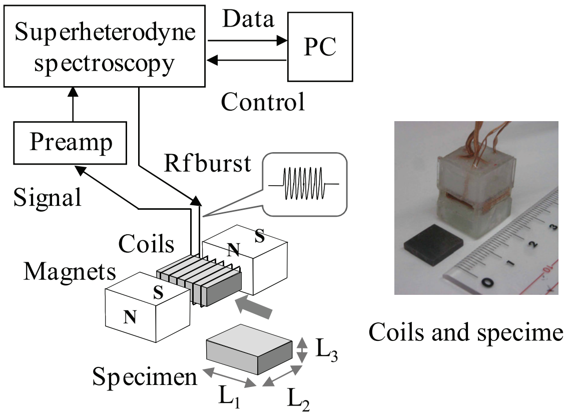
1. Introduction

Reactor pressure vessels (RPVs) in nuclear power plants (NPPs) are embrittled during the operation due to the formation of irradiation defects by netutron bombardment[1-3]. The clarification of the degradation mechanism and the development of nondestructive evaluation (NDE) techniques are important for prolonging the lifetime of present NPPs. Several NDE methods have been investigated and ultrasonic characterization is one of the candidates. It has been reported that the ultrasonic attenuation of simple metals is reduced by irradiation because the irradiation defects impede dislocation movement and they supress the dislocation damping effects[4]. However, the attenuation behavior is not clear in the case of neutron-irradiated RPV steels which have complex metallurgical microstructures[5, 6]. Most of the previous studies were carried out by conventional ultrasonic methods using a piezoelectric transducer that inherently includes contact problems. In order to clarify the irradiation effects of RPV steels, precise measurement is necessity to suppress data scatter and improve reliability. Recently, an electromagnetic acoustic resonance (EMAR) method, a contactless measurement, attracts much attention in precise ultrasonic characterization [7, 8]. The purpose of this study is to develop an EMAR system for the measurement of neutron irradiated specimens and investigate the irradiation effects on ultrasonic attenuation.

2. Experimental Procedure

Small plate-shaped specimens ($L_1 \times L_2 \times L_3$= 11.5 mm × 12 mm × 2.0 mm) for small angle neutron scattering (SANZ) measurement were used for EMAR measurement. The specimens were neutron-irradiated in various conditions under the University of California, Santa Barbara (UCSB) irradiation variable (IVAR) program [9]. In this study, we examined A533B type RPV steel (Cu content: 0.42wt%) irradiated at 290℃ up to the neutron fluence of 3×10^{19}cm^{-2}. **Figure 1** shows the setup for EMAR measurement and the specimen orientation. The specimen is inserted into the exciting and detecting coils located between the magnets. These are the specially designed coils and magnets for the measurement of irradiated specimens in order to realize an easy-handling of the radioactive specimens and prevent the measurement system from radioactive contamination. In the case of ferromagnetic metals, elastic waves are excited by dynamic magnetic fields from an RF burst current through the magnetostriction mechanism [7]. The signal of the excited vibration was detected by the coil and pre-amplified. Amplitude and phase information of the signal were acquired by a personal computer through analog superheterodyne processing. All the above measurements were carried out using a RITEC RAM system at the facility of UCSB for post-irradiation examination.



Coils and specimen

Fig. 1 Schematic representation and picture of the measurement setup and the specimen orientation.

3. Results and Discussion

Figure 2 shows typical EMAR spectrum of an unirradiated specimen. Periodic resonant peaks appear clearly, originating from the resonance of shear wave. The peak frequency of *n*th mode (*n* is an integer), f_n, can be described by the following

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equation:

$$f_n = (2n+1)\cdot v_s / 2L_2$$

The attenuation coefficient, α, was obtained by determining of a precise resonant frequency, obtaining the ring-down curve, then fitting to an exponential decay function [7, 8]. **Figure 3** shows a typical ring-down curve at the resonant peak of n = 15 in Fig. 2. In this study, the attenuation coefficients at the resonant peaks from 1 to 5MHz were evaluated and then averaged to highlight the irradiation effect. The dependence of the averaged attenuation coefficient against neutron fluence is summarized in **Figure 4**, together with the data on yield stress increment [9]. It has been known that yield stress increases with increasing neutron fluence due to the formation of irradiation defects such as Cu-rich precipitates and dislocation loops [1-3]. Fig. 4 also shows a slightly increasing behavior of α, which is different to the decreasing behavior previously observed in the γ-ray irradiated simple metals [4]. This phenomenon would be related to the complex metallurgical and irradiation defect structure of RPV steel, and further studies are desirable to understand the details of the mechanism.

4. Conclusion

We developed an EMAR measurement system for radioactive specimens and the attenuation coefficients of neutron-irradiated RPV steels were evaluated. The neutron fluence dependence of attenuation coefficient showed an increasing behavior, which is different from the decreasing trend of the simple metals. This study suggests a possibility of the application of the EMAR method for NDE of irradiation embrittlement of RPV steels.

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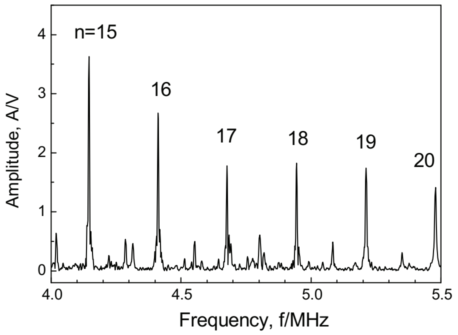

Fig. 2 Typical EMAR spectrum.

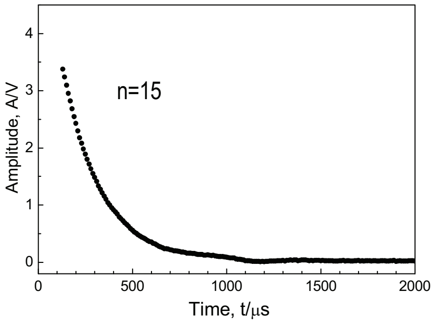

Fig. 3 Typical ring-down curve.

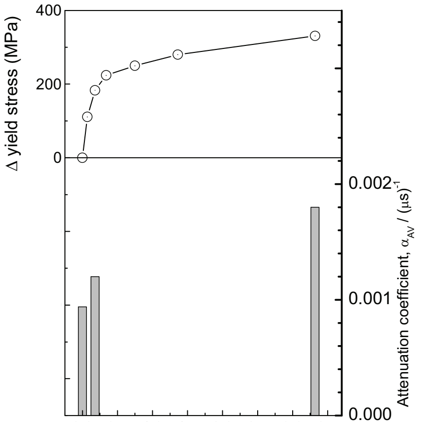

Fig. 4 Neutron fluence dependence of attenuation coefficient and yield stress.