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Round-Robin NDE Testing for Charpy Impact Specimens of Cold-rolled and Thermally Aged Fe–1wt.%Cu Alloys

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Abstract

Results are briefly shown for round-robin non-destructive evaluation (NDE) testing of Charpy impact specimens of cold-rolled and thermally aged Fe–Cu alloys, which were model specimens used to simulate irradiation embrittlement of nuclear reactor pressure vessel (RPV) steels. Magnetic, thermoelectric and ultrasonic NDE measurements were performed using the same specimens. The coercive force was sensitive to change in the dislocation state, whereas thermoelectric power was sensitive to change in that matrix state. The velocity of ultrasound waves also seemed to be influenced by the matrix state. The combination of these techniques would utilize the advantages of the different methods and compensate for the weaknesses. This study suggests the importance of the combined usage in establishing reliable NDE procedures for the determination of degradation of irradiated RPV steels.

Keywords: irradiation embrittlement, magnetism, thermoelectric power, ultrasound resonance

1. Introduction

Irradiation embrittlement of nuclear reactor pressure vessels (RPVs) is a great concern for the safe operation of nuclear power plants (NPPs). Current methods to ensure RPV integrity are based on measurements of the ductile–brittle transition temperature (DBTT) of surveillance specimens obtained by destructive Charpy impact testing. However, with the extended lifetimes of NPPs, there will be a shortage of the surveillance test pieces, and therefore the development of nondestructive evaluation (NDE) techniques is strongly required. Several physical properties, reflecting the formation of irradiation defects, are applicable as the parameters for such NDE techniques. To date, magnetic hysteresis curves [1, 2], thermoelectric power [3], and ultrasound velocity and attenuation [4, 5] of the irradiated RPV steels have been investigated, and changes in each property have been confirmed. However, the correlation mechanism between an NDE parameter and the irradiated microstructure, and that between the DBTT and microstructure are not always the same, which may restrict the application in some cases. Therefore, these techniques need to be compared and the characteristics clarified to establish reliable NDE procedures. The aim of this study is to assess the feasibility of applying the three above NDE techniques and compare underlying correlation mechanisms by round-robin analysis using common Charpy specimens to simulate the irradiated RPV steels.

2. Preparation of Test Specimens

In this study, Fe–1wt.%Cu model alloys were prepared since Cu precipitation is one of the sources of the irradiation embrittlement of RPV steels [6]. The model alloys were quenched from 850^{o}C and cut into full-size V-notch Charpy test specimens (55mm × 10mm × 10mm). Four types of specimens were adopted as shown in Table 1. The first was an as-quenched specimen, Sp.A (AQ), a supersaturated solid-solution state of Cu. The second was a 40% cold-rolled specimen, Sp.B (CR), prepared so we can investigate the effect of dislocation. The third was a cold-rolled and thermally-aged specimen, Sp.C (CR+TA), prepared for simulating the combined effects possibly occurring in the irradiated RPV steels. The fourth was a simply thermal-aged specimen, Sp.D (TA), prepared for clarifying Cu precipitation effects. Thermal-aging was carried out at 500^{o}C for 10^3 min, which is the condition for reaching maximum hardness due to Cu precipitation [7]. The DBTT of each specimen obtained by Charpy impact testing is summarized in Table 1 [8]. The DBTT increased with CR and TA treatment and the specimens became embrittled owing to the increase in dislocation density and the formation of Cu precipitates respectively. The DBTT of Sp.C was the highest and above the measuring limit of the test system (>80 ^{o}C). Using these Charpy specimens, magnetic, thermoelectric and ultrasonic NDE measurements were carried out.

Table 1 Preparation conditions and DBTT of the each specimen.

Specimen	Cold-rolled 40%	Thermally-aged 500℃,10^3min	DBTT (℃)
A (AQ)	–	–	0
B (CR)	○	–	23
C (CR+TA)	○	○	> 80
D (TA)	–	○	68

3. Results and Discussion

Fig. 1 shows a schematic representation of the setup for the magnetic measurement. The apparatus was specially designed for the measurement of an induced magnetic flux density – magnetic field (*B*–*H*) loop of full-size Charpy specimens at a hot lab facility. It consists of a Fe–Si yoke, permendur support rods, and exciting and detecting coils. Signal detected by *B*–coil and *H*–coil were digitalized and a *B*–*H* curve was obtained using the software LabVIEW. Details of the measurement procedures and conditions are given in another paper [9]. Fig. 2 summarizes the relation between the coercive force obtained from *B*–*H* curves and DBTT. Two points are worthy of note: the different effects of cold-rolling and thermal-aging on the coercive force, and the effect of pre-deformation before thermal-aging. Regarding the former point, both the coercive forces of Sp.B and Sp.D were greater than that of Sp.A; however, the coercive force for Sp.B was larger than that for Sp.D, which means the magnetic parameter is more sensitive to the formation of a dislocation than to Cu precipitation. Regarding the latter, the coercive force for Sp.C was smaller than that for Sp.B though the DBTT of Sp.C was higher than that of Sp.B. A possible reason for of the weaker coercive force of Sp.C is the compensation of internal stress due to the formation of Cu precipitates in the vicinity of the dislocation [1]. Evaluation of the precipitate formation along the dislocation is important because dislocation movement would be preferentially hindered by such precipitates. Using the magnetic NDE method is advantageous in the evaluation of such a dislocation state; however, there is a complicated correlation between the DBTT and coercive force (Fig. 2).

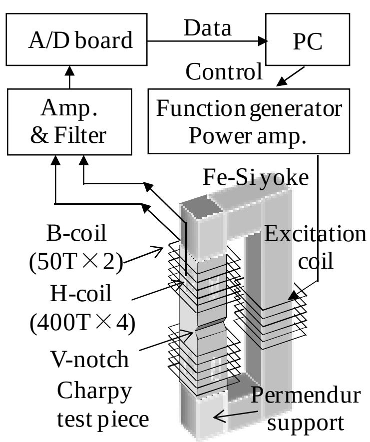

Fig. 1 Schematic representation of the setup for the magnetic measurement.

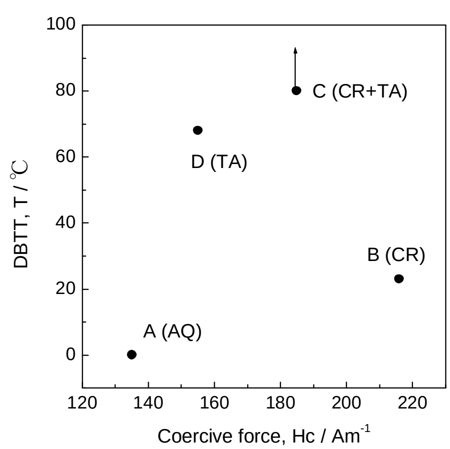

Fig. 2 Relation between coercive force and DBTT.

Fig. 3 shows a schematic representation of the setup for the thermoelectric power (TEP) measurement [10, 11]. The system can be used for measuring TEP of field materials in NPPs. Two copper prods with a temperature difference ΔT were placed on the Charpy specimens, and an electrical potential difference ΔV was measured. The TEP is defined as $\Delta V / \Delta T$, and was measured at 20 points for each 55 mm × 10 mm surface area by moving the hot prod. A total of

80 data were thus obtained for each specimen and they were averaged. Fig. 4 summarizes the relation between TEP and DBTT. The TEP data for the four specimens can be classified into two groups: thermally-aged and un-aged data. TEPs of Sp.C and Sp.D were higher than those of Sp.A and Sp.B. This phenomenon is related to the depletion of Cu solute atoms in matrix during Cu precipitation [10]. Contrarily, the difference in TEP between Sp.A and Sp.B, and that between Sp.C and Sp.D were small. These results indicate that TEP is far more sensitive to the matrix state than to the dislocation state. Roughly speaking, the DBTT of the present specimens increased with increasing TEP value. Therefore, the correlation between the DBTT and TEP appears relatively simple, and TEP measurement seems to be a powerful NDE tool for determining embrittlement, when a solute depletion occurs during degradation process.

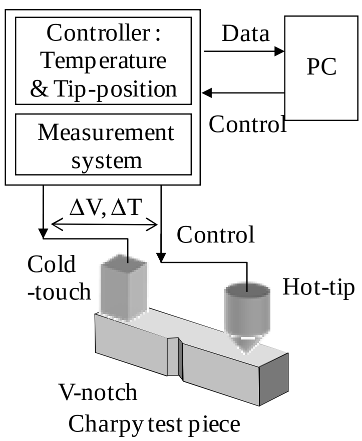

Fig. 3 Schematic representation of the setup for the TEP measurement.

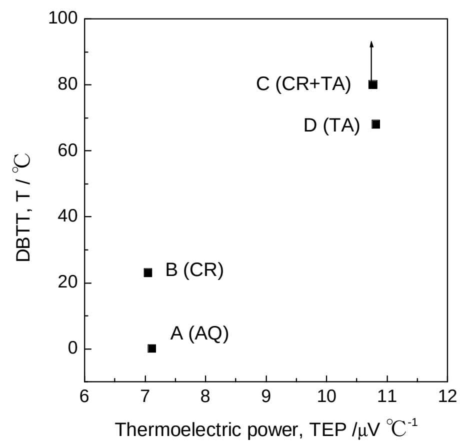

Fig. 4 Relation between TEP and DBTT.

For the characterization of ultrasound properties, an electromagnetic acoustic resonance (EMAR) method was used to achieve precise measurement [12, 13]. Fig. 5 shows a schematic representation of the setup for EMAR measurement. The Charpy specimen was inserted into the coils located between the two poles of a magnet. In the case of ferromagnetic metals, ultrasound waves are excited by dynamic magnetic fields from a radio frequency burst current via magnetostrictive effect [12]. All the measurements were carried out using a RITEC RAM system. Fig. 6 shows the EMAR spectra of the present Sp.A together with that of another as-quenched specimen. Regarding the present round-robin specimens, clear EMAR spectra could not be obtained as shown in Fig.6 (a). This is attributable to scattering by the coarse grains of the present specimens (with size about 1 mm). Contrarily, several periodic peaks due to thickness resonance were confirmed using a Charpy specimen with same specimen size but smaller grain size (about a hundred microns) as shown in Fig. 6 (b). The EMAR experiment using the Fe–Cu alloy specimens with fine grains showed the shear wave velocity increased with increasing thermal-aging time, which is related to the increase in elastic constant due to Cu solute depletion in the matrix [13]. An ultrasound measurement would be feasible for the NDE of irradiation degradation.

The present study shows the feasibility and characteristics of each NDE technique. The mechanism of irradiation embrittlement is not simple [6], and an increase in DBTT could be induced by different microstructural changes. The combination of NDE techniques could utilize the advantages of different methods, and compensate for the weaknesses, and hence overcome the complexity of the NDE of degradation of actual irradiated RPV steels.

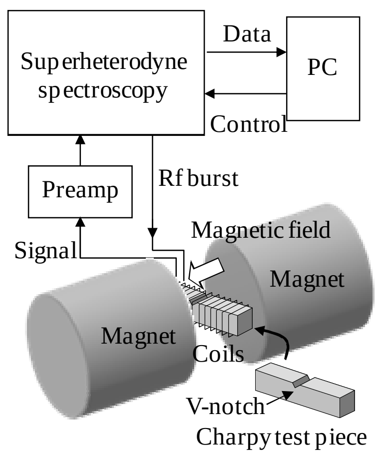

Fig. 5 Schematic representation of the setup for the EMAR measurement.

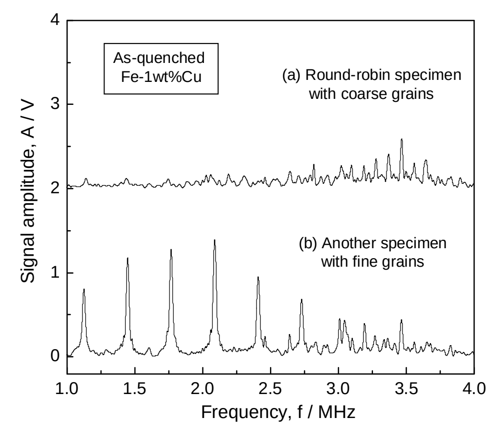

Fig. 6 EMAR spectra of as-quenched specimens.

4. Conclusion

Round-robin NDE testing was performed for cold-rolled and thermally-aged Fe–1wt.%Cu model alloys, which were used to simulate irradiation embrittlement, using different NDE techniques. Magnetic NDE is sensitive to change in the dislocation state, whereas TEP measurement is sensitive to change of the matrix state. The use of ultrasound is also feasible. It is important to combine these techniques to establish reliable NDE procedures.

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