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A preliminary evaluation of irradiation damage in model alloys by electric properties based techniques

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Abstract

The most important effect of the degradation by neutron irradiation is a decrease in the ductility of reactor pressure vessel (RPV) ferritic steels. The main way to determine the mechanical behaviour of the RPV steels is tensile and impact tests, from which the ductile to brittle transition temperature and its increase due to neutron irradiation can be calculated. These tests are destructive and are regularly applied to surveillance specimens to assess the integrity of the RPV. The possibility of applying validated non-destructive aging monitoring techniques would however facilitate the surveillance of the materials that form the reactor vessel.

The Institute for Energy of the Joint Research Centre has developed two devices, focussed on the measurement of the electrical properties which prove to give a good non-destructive assessment of the embrittlement state of ferritic steels. The first technique, called Seebeck and Thomson Effects on Aged Material (STEAM), is based on the measurement of the Seebeck coefficient, characteristic of the material and related to the microstructural changes induced by irradiation embrittlement. With the same aim, the second technique, named Resistivity Effects on Aged Material (REAM), measures instead the resistivity of the material.

This paper explains (i) preliminary STEAM and REAM results and (ii) results compared with Charpy impact energy temperature shifts due to neutron irradiation. These results will make possible the improvement of such techniques based on the measurement of material electrical properties for their application to non-destructive irradiation embrittlement assessment.

Keywords: Reactor pressure vessel steel; Irradiation damage; Non-destructive techniques; Ageing monitoring; Thermo-electric power

1. Background

Neutron irradiation affects the microstructure of steels by inducing matrix defects (copper precipitates, interstititials and voids) and segregation of elements and impurities to grain boundaries, hence causing embrittlement of the nuclear reactor pressure vessels (RPV) ferritic steels The main parameters affecting materials' sensitivity to neutron embrittlement are chemical composition, heat treatment, neutron fluence and fluence rate and irradiation temperature.

The integrity of the RPV is assessed by periodic non-destructive inspections and by vessel surveillance programmes imposed by the licensing regulations as standard practices [1]. These require periodic evaluation at different neutron fluences of tensile properties, impact energy and fracture toughness by tests carried out on sacrificial specimens of the same base and weld RPV metal irradiated in-core in proper surveillance capsules. These are characterised by higher lead factor, i.e. neutron higher fluence rate than the RPV, to allow quicker embrittlement and therefore evaluation of the actual RPV ahead of time. The availability of these specimens is of course limited, due to with progressive testing and removal from the core, which could be a limiting factor for license extension of the nuclear power plant.

A non-destructive determination of the embrittlement state would extend the usefulness of the surveillance material by reducing the material used for destructive studies and would benefit surveillance programmes having insufficient available test material, and ultimately allow tests to be performed directly on a component.

There is therefore a need to develop techniques that allow an early detection of microstructural changes due to embrittlement. In the particular case of nuclear power plants, the effect of the neutron irradiation in the beltline

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area of the RPV should be assessed. Non-destructive evaluation (NDE) methods capable of identifying the level of irradiation embrittlement would be the most desirable. Such NDE capabilities would provide substantial early warning of component deterioration and enable utilities to optimise their operating and maintenance practices, resulting in reduced costs and increased asset utilisation [2].

A possible utilisation would be in hot cell, in parallel to impact or fracture toughness testing, or as an alternative to them if properly validated, thus allowing re-insertion of the specimens into the surveillance capsule.

For these techniques, there is not only the requirement of damage detection capability, but also the need to improve the non-destructive systems in the sense of simplicity of operation, speed, accuracy of measurement and cost. Another important issue needing more research on NDE is the possibility of forecasting the material degradation on the basis of the actual material condition. As a first step, relationships between the ageing conditions (temperature, time, irradiation fluence, etc.), the material properties and the results of non-destructive analysis must be computed. Afterwards embrittlement trend curves similar to those produced for destructive testing (i.e. those provided in the regulatory guides of NRC) should be developed.

2. Experimental procedure

As described hereinafter, measurements of thermoelectric power (STEAM) and resistivity (REAM) have been performed on model alloys in virgin and irradiated conditions, and then compared with the results of Charpy impact testing.

2.1. Materials

The materials tested were Model Alloys provided by the Kurchatov Institute, covering a large spectrum of compositions typical of ferritic steel with parametric variation of copper, nickel and phosphorus, elements known to play a significant role in material sensitivity to irradiation [3]

Typical composition ranges used are: Ni 0–2%, P 0–0.04% and Cu up to 1%, Mn 0.4%, low S and balance content of Fe. Table 1 shows the Cu, Ni, P and other element contents.

All the alloys followed the same heat treatment: quenching at 980–1000 °C, oil cooling, followed by tempering at 650–670 °C for 10 h, and then cooled in air. The specimens were machined as miniaturised Charpy ones ($3 \times 4 \times 27$ mm^3) and characterised by Charpy impact tests, STEAM and REAM techniques.

The specimens were irradiated in the High Flux Reactor, at Petten (The Netherlands), in the LYRA irradiation rig, used in several projects organised by the Ageing Materials European Strategy (AMES) Network [4]. The irradiation was carried out at 270 °C, reaching an accumulated fluence of about 6.11×10^{22} N/m^2 ($\sim$0.1 displacements per atom).

2.2. Measurements of the relative Seebeck coefficient—steam technique

References to previous studies of thermoelectric power effects in materials and their application to NDE of metals can be found in Refs. [5–11]. Based on these experiences, the Institute for Energy of the Joint Research Centre (JRC-IE) has developed the Seebeck and Thomson Effects on Aged Materials (STEAM) laboratory prototype with the aim

Table 1
Composition of the model alloys

Block number	Ni (wt%)	Cu (wt%)	P (wt%)	C (wt%)	Si (wt%)	Al (wt%)	Cr (wt%)	Mn (wt%)	Mo (wt%)	W (wt%)	V (wt%)	Ti (wt%)	S (wt%)	Co (wt%)
185	2.0	0.4	0.037	0.006	0.14	0.016	0.009	0.46	0.004	0.01	<0.003	0.002	0.002	0.005
184	2.0	0.4	0.008	0.002	0.11	0.016	0.009	0.44	0.004	0.007	<0.003	0.002	0.001	0.042
181	2.0	0.1	0.006	0.001	0.07	<0.002	0.008	0.35	0.004	0.004	<0.003	0.002	0.002	0.004
183	2.0	0.4	0.002	0.004	0.16	0.014	0.008	0.46	0.004	0.009	<0.003	0.002	0.002	0.009
180	2.0	0.1	0.001	0.002	0.13	0.004	0.01	0.45	0.004	<0.003	<0.003	0.002	0.002	0.003
179	2.0	0.0	0.001	0.002	0.15	0.006	0.009	0.45	0.004	0.006	<0.003	0.002	0.001	0.005
176	1.1	0.1	0.037	0.005	0.19	0.007	0.009	0.46	0.004	0.008	<0.003	0.002	0.002	0.003
178	1.2	0.4	0.009	0.003	0.2	0.019	0.01	0.48	0.005	0.006	<0.003	0.002	0.002	0.003
177	1.2	0.4	0.002	0.003	0.19	0.011	0.028	0.45	0.004	0.009	<0.003	0.002	0.002	0.003
443	1.2	0.0	0.001	0.002	0.27	0.007	0.011	0.5	0.005	<0.003	<0.003	0.002	0.001	<0.003
444	1.2	0.1	0.001	0.001	0.22	0.006	0.01	0.49	0.004	<0.003	0.004	0.002	0.002	<0.003
441	0.7	0.4	0.011	0.001	0.21	0.01	0.011	0.5	0.004	<0.003	<0.003	0.002	0.001	<0.003
440	0.7	0.4	0.002	0.001	0.17	<0.003	0.011	0.47	0.004	<0.003	<0.003	0.002	0.001	<0.003
435	0.004	1.0	0.037	0.002	0.11	<0.002	0.014	0.39	0.004	<0.003	<0.003	0.002	0.003	<0.003
643	0.004	1.0	0.011	0.007	0.26	0.006	0.027	0.52	0.007	<0.003	<0.003	0.002	0.002	<0.003
640	0.004	0.4	0.012	0.001	0.24	0.051	0.012	0.49	0.005	<0.003	<0.003	0.002	0.003	<0.003
638	0.007	0.1	0.035	0.001	0.22	0.059	0.019	0.48	0.007	<0.003	<0.003	0.002	0.003	0.008
641	0.003	1.0	0.002	0.001	0.17	0.037	0.01	0.45	0.005	<0.003	<0.003	0.024	0.004	<0.003
642	0.005	0.4	0.031	0.001	0.17	0.02	0.011	0.44	0.004	<0.003	<0.003	0.029	0.003	<0.003