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Radiation intensification of the reactor pressure vessels recovery by low temperature heat treatment (wet annealing)

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Abstract. As a main barrier against radioactivity outlet reactor pressure vessel (RPV) is a key component in terms of NPP safety. Therefore present-day demands in RPV reliability enhance have to be met by all possible actions for RPV in-service embrittlement mitigation. Annealing treatment is known to be the effective measure to restore the RPV metal properties deteriorated by neutron irradiation.
There are two approaches to annealing. The first one is so-called «dry» high temperature (~475°C) annealing. It allows obtaining practically complete recovery, but requires the removal of the reactor core and internals. External heat source (furnace) is required to carry out RPV heat treatment.
The alternative approach is to anneal RPV at a maximum coolant temperature which can be obtained using the reactor core or primary circuit pumps while operating within the RPV design limits. This low temperature «wet» annealing, although it cannot be expected to produce complete recovery, is more attractive from the practical point of view especially in cases when the removal of the internals is impossible.

1. Introduction

Modern nuclear power engineering is based on LWR type plant reactors. As a main barrier against radioactivity outlet reactor pressure vessel is a key component in terms of NPP safety. Therefore present-day demands in RPV reliability enhance have to be met by all possible actions for RPV in-service embrittlement mitigation. Annealing treatment is known to be the effective measure

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The alternative approach is to anneal RPV at a maximum coolant temperature which can be obtained using the reactor core or primary circuit pumps while operating within the RPV design limits. This low temperature «wet» annealing, although it cannot be expected to produce complete recovery, is more attractive from the practical point of view especially in cases when the removal of the internals is impossible.

As a rule there is no recovery effect up to annealing and irradiation temperature difference of 70°C. It is known, however, that along with radiation embrittlement neutron irradiation may mitigate the radiation damage in metals. Therefore we have tried to test the possibility to use the effect of radiation-induced ductilization in «wet» annealing technology by means of nuclear heat utilization as heat and neutron irradiation sources at once.

2. Prerequisites to the substantiation of RPV embrittlement controlling through wet annealing

Irradiated metal condition after annealing can be expressed in terms of recovery index (RI) by the following dependence: $RI=(TT_{irr}- TT_{ann})/(TT_{irr}- TT_{init})$,
where TT_{irr}, TT_{ann}, and TT_{init} are ductile-to-brittle transition temperatures (DBTT) of the metal in the irradiated, annealed and initial conditions respectively.

RI variation as a function of furnace annealing and irradiation temperatures (T_{ann} and T_{irr}=270°C) respectively) difference at a holding duration of 100 h for Russian 15Cr2MoV type RPV steel irradiated at the fast neutron (E≥0,5 MeV) fluxes from 5×10^{10}sm^{-2}s^{-1} to 3×10^{12}sm^{-2}s^{-1} in NPP reactors is presented in [1]: there are no recovery effect up to annealing and irradiation temperature difference of 70°C while T_{ann}=340°C (T_{irr}+70°C) is practically maximum accessible value for wet annealing technology.

The first RPVs «wet» annealing were done using nuclear heat (US Army SM-1A) or primary pump heat (Belgian BR-3). The annealing temperature in the former case was 293-300°C (72-79°C above the service temperature). The degree of recovery in this case was about 70%. In the BR-3 reactor the service temperature was 260°C and the vessel was annealed at 343°C. The recovery was estimated to beat least 50%. The planned annealing of the Yankee Rowe vessel at 343°C (83°C above the service temperature) was estimated to give a 45-55% recovery [2].

The "wet" annealing technique is easy to implement because there is no need to remove fuel from the RPV, but it can be effectively utilized only in reactors which have a relatively low service temperature. Due to limited recovery, «wet» annealing with primary water is not a practical solution for power reactors or it needs to be frequently repeated.

It is known, however, that along with radiation embrittlement neutron irradiation may mitigate radiation damages in metals [3]. Therefore we have tried to study the possibility to use this effect in «wet» annealing technology by means of nuclear heat utilization as heat and neutron irradiation sources at once.

3. Experimental procedures and test results

In support of the above-mentioned conception the 3-year duration reactor experiment on RPV steel was carried out.

Material. Metal used for the studies described here is RPV steel of the 15Cr3NiMoV-A type. Table 1 provides the chemical composition of the metal.

Table 1. RPV steel chemical composition (wt. %%).

C	P	Cu	Cr	Mo	Ni
0,14	0,009	0,08	2,00	0,90	1,15

Irradiation. Preliminary (primary) irradiation was carried out in the commercial power plant. Cylindrical billets of the steel were placed into the perforated stainless steel capsules and therefore were irradiated in direct contact with running primary water. Full size and sub size Charpy type specimens were manufactured from irradiated billets by means of electro discharge machining (EDM).

To examine «wet» annealing potentiality, experiment on effectiveness of the irradiated RPV steel extra irradiation was conducted. Pre-irradiated to 9×10^{19}sm^{-2} (E>0,5MeV) at a nominal temperature of 270°C metal was additionally extra irradiated in test reactor IR-8 at 330°C at neutron flux level of 3×10^{11}sm^{-2}s^{-1} (E≥0,5MeV) during 86,7 hours (fluence ~10^{17}sm^{-2}). Figure 1 represents result obtained.

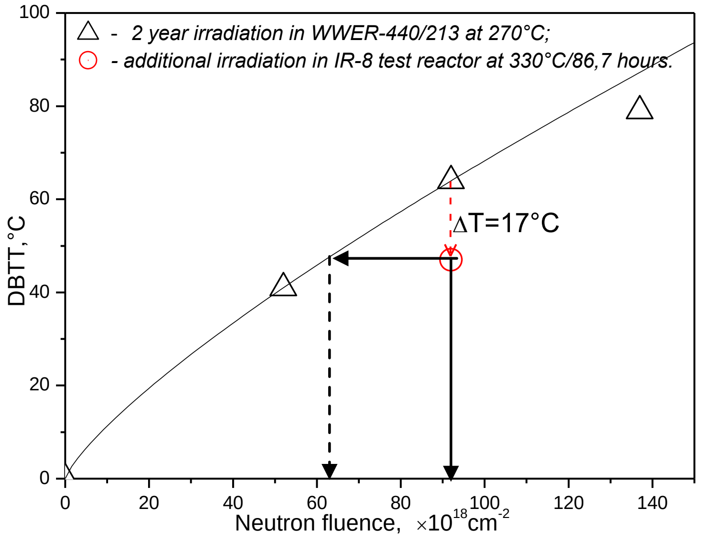

Figure 1. Result of the experiment on potential effectiveness of the RPV «wet» annealing.

One can see that despite the presence of irradiation during annealing treatment reduction of the transition temperature (DBTT) took place. In fact, embrittlement was partly suppressed up to value equivalent to 1,5 fold neutron fluence decrease.

4. Discussion

In connection with data received question of enhanced annealing effectiveness at the presence of the neutron field arise. One can imagine that during heat treatment at the presence of the neutron field annealing competes with damage process and exceeds it that result in recovery. Possibly neutron bombardment during heat treatment reduces the hardening efficiency of the existing precipitates. Figure 2 represents dependence of the precipitate hardening efficiency on dimension of the features [4] that act as obstacles to dislocation glide.

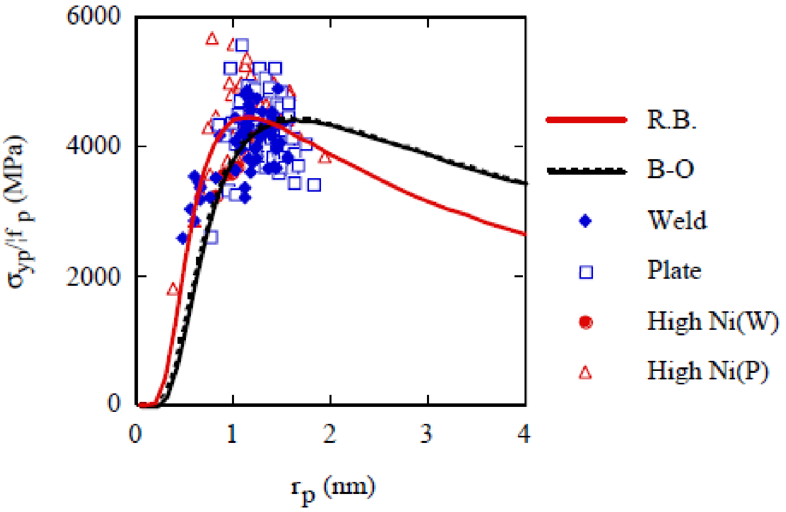

Figure 2. The precipitate hardening efficiency versus feature dimension (radius) showing both the Russell-Brown (RB) model along with the Bacon-Osetsky (BO) model.

It is seen that turning point are at the area of the 1,5 nm and that left branch is very sharp. Hypothetically neutron bombardment leads to partial precipitates dissolution that in turn results in their hardening efficiency reduction.

In this context one can remember that there are data on beneficial effect on mild steel properties of low dose neutron irradiation at 80°C up to fast neutron fluencies of 3,9×10^{16}sm^{-2}; 2,8×10^{17}sm^{-2}; 2,0×10^{18}sm^{-2} and 1,4×10^{19}sm^{-2} (E≥1MэВ) [4]. Composition of this steel is given in table 2.

Table 2. Chemical composition of the steel examined (%% mass.).

C	Si	Mn	S	Cu	Cr	Mo	Ni	N	O
0,05	0,001	0,39	0,012	0,09	0,04	0,16	0,03	0,004	0,012

Original load-elongation curves of mild steel observed at 100°C are reproduced in Figure 3.

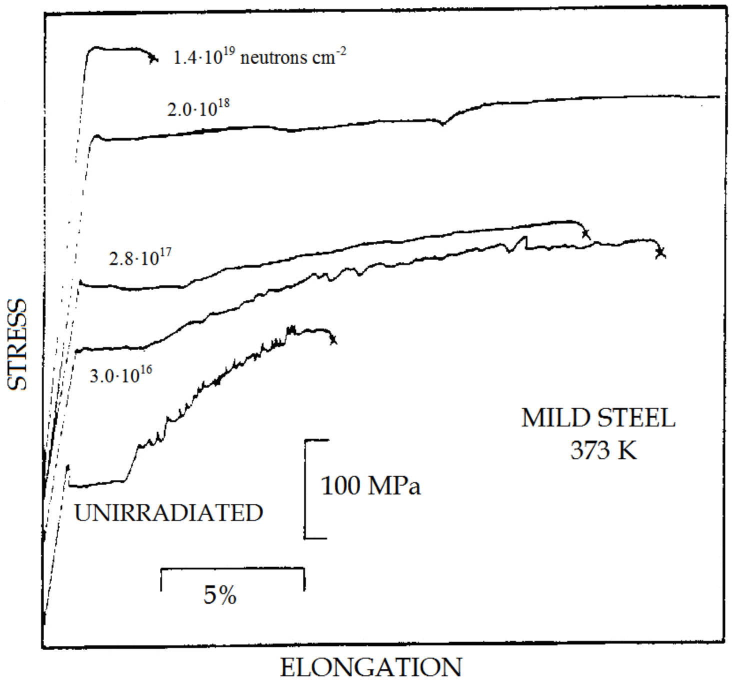

Figure 3. Load-elongation curves of mild steel observed at 100°C.

One can see that irradiation up to neutron fluence of 2,0×10^{18}sm^{-2} improved both the mechanical strength and ductility. In our case steel was extra irradiated in test reactor IR-8 up to fast neutron fluence ~10^{17}sm^{-2} for E≥0,5MeV and roughly 6×10^{17}sm^{-2} for E≥1MeV, that is in good conformity with data depicted in Figure 3.

Similar effect of the radiation-induced ductilization was recorded for Ti47Al alloy [5].

Thus it is possible to suppose that just neutron field by means of cascade dissolution of the existing radiation defects at low doses can bring to beneficial modification of the steel mechanical properties.

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