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Mechanical properties and microstructure of long term thermal aged WWER 440 RPV steel

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HIGHLIGHTS

- The influence of long term thermal ageing of WWER-440 RPV steel weld was studied.
- No differences in tensile and impact properties after 27 years of thermal ageing.
- The phase composition of the microstructure didn't change significantly.
- Minor changes observed in microstructure didn't influence mechanical properties.
- Fracture morphology remained essentially same after long term thermal ageing.

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ABSTRACT

The integrity assessment of the Reactor Pressure Vessel (RPV) is essential for the safe and Long Term Operation (LTO) of a Nuclear Power Plant (NPP). Hardening and embrittlement of RPV caused by neutron irradiation and thermal ageing are main reasons for mechanical properties degradation during the operation of an NPP. The thermal ageing-induced degradation of RPV steels becomes more significant with extended operational lives of NPPs. Consequently, the evaluation of thermal ageing effects is important for the structural integrity assessments required for the lifetime extension of NPPs.

As a part of NRG's research programme on Structural Materials for safe-LTO of Light Water Reactor (LWR) RPVs, WWER-440 surveillance specimens, which have been thermal aged for 27 years (~200,000 h) at 290 °C in a surveillance channel of Armenian-NPP, are investigated. Results from the mechanical and microstructural examination of these thermal aged specimens are presented in this article.

The results indicate the absence of significant long term thermal ageing effect of 15Cr2MoV-A steel. No age hardening was detected in aged tensile specimens compared with the as-received condition. There is no difference between the impact properties of as-received and thermal aged weld metals. The upper shelf energy of the aged steel remains the same as for the as-received material at a rather high level of about 120 J. The T_{41} value did not change and was found to be about 10 °C. The microstructure of thermal aged weld, consisting carbides, carbonitrides and manganese-silicon inclusions, did not change significantly compared to as-received state. Grain-boundary segregation of phosphorus in long term aged weld is not significant either which has been confirmed by the absence of intergranular fracture increase in the weld. Negligible hardening and embrittlement observed after such long term thermal ageing is attributed to the optimum chemical composition of 15Cr2MoV-A for high thermal stability.

1. Introduction

The Reactor Pressure Vessel is a key component of the Nuclear

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Power Plant. The integrity assessment of the RPV is one of the main issues for the safe and long term operation of NPPs. The main reason for the degradation of RPV mechanical properties is neutron irradiation during the operation of NPP. These conditions cause hardening and embrittlement of the RPV steel. The prediction of hardening and embrittlement is usually performed in accordance with relevant codes and standards that are based on a large amount of information from surveillance and research programmes. Current regulatory practices for RPV lifetime prediction rely primarily on information gained from surveillance programmes of power reactors.

Several sets of surveillance specimens fabricated from the same shells and welds of the reactor pressure vessel, are typically placed into the surveillance channels of the reactor. A periodical withdrawing of the designated set is performed to investigate degradation of RPV mechanical properties due to thermal ageing and neutron irradiation. The total embrittlement effects, as often quantified by the absolute values of shifts in the ductile-to-brittle transition temperature values (T_k) of RPV steel, are estimated by comparison of irradiated and as-received specimens testing results.

As most of the existing NPPs are considering for extending their operation life, the thermal ageing-induced degradation of RPV steels (in addition to the irradiation induced degradation) becomes more significant. Several investigations of long term thermal ageing induced effects on WWER and LWR RPV steels were reported in the literature [1–5]. For instance, Gunawardene et al. [4]. investigated mechanical property changes in three different LWR RPV materials (SA-508 Class 2 forging, a Mn-Mc-Ni Linde 80 submerged-arc weld, and an SA-533, Grade B, Class 1) thermally aged for 209,000 h at 282 °C. Only minor changes in the impact and fracture toughness properties were reported for all the materials investigated in this study. Similarly, Chernobaeva et al. [3]. found absence of hardening effects due to thermal aging between 310 and 320 °C for WWER-1000 RPV weld metal. Conversely, thermal ageing induced embrittlement was reported in WWER-1000 RPV steels constituting nickel content greater than 1.35% [1,2].

In this respect, both thermal ageing and irradiation effects should be evaluated to perform structural integrity assessments for the lifetime extension of NPPs. Another important open issue in the RPV steel degradation prediction is to understand whether the embrittlement mechanisms of thermal ageing and irradiation have any synergetic effects or these effects are just additive. In this sense, the study of surveillance sets containing both the long term irradiated and thermal aged materials assumes primary importance. Consequently, surveillance programmes of (some) NPPs introduce separate sets of RPV steel specimens to monitor embrittlement behaviour due to both thermal ageing and neutron irradiation.

Extensive microstructural research has been conducted in the past by transmission electron microscopy (TEM) and atom probe tomography (ATP), on WWER-440 RPV steels in *as–received, irradiated and thermal aged conditions* [6–8]. No significant changes in the microstructure were observed after thermal ageing up to a maximum of 90,000 h (~10 years) at 295 °C, when compared with the as-received steels. However, to the authors knowledge, the influence of thermal ageing on these steels for greater than 90,000 h was not documented in the literature, which is of great importance for the safe long term operation of NPPs. In this respect, the current study focus on investigating the influence of thermal ageing at a longer ageing time, i.e. for ~200,000 h, for WWER-440 steels.

In the framework of cooperation between NRG, Armenian NPP and research institute Armatom [9], the last chain of Armenian surveillance programme was withdrawn in 2012 after irradiation for 27 years (~200,000 h) and transported to NRG (Petten, The Netherlands) for investigation. The chain consists of irradiated and thermal aged parts. The mechanical and microstructural characterization results from thermal aged specimens are presented in the current publication. The research on irradiated specimens is in progress and will be published later. The mechanical testing of thermal aged surveillance specimens was performed in the laboratories of NRG and JRC-IET. The hardening and embrittlement behaviour of base metal, welds and Heat Affected Zone (HAZ) specimens are characterized by tensile, KLST (mini-charpy) and full size Charpy testing. Additionally, SEM and TEM microstructural investigation of as-received and thermal aged specimens are performed to understand any embrittlement mechanisms and explain the mechanical testing results.

2. Materials of Armenian RPV surveillance programme

The 440 MWe Water Water Energy Reactor (WWER-440) in Armenia was put into operation by the end of 1979. The WWER pressure vessel materials differ from the Western RPV steels. The chromium-molybdenum-vanadium steel grade 15Cr2MoV-A used for the WWER-440 pressure vessels contains ~0.3 wt percent vanadium and very little nickel (maximum of 0.40 wt%). The steel with vanadium alloying was used because the vanadium carbides make the material relatively resistant to thermal ageing, fine grained (tempered bainite) and strong. However, the 15Cr2MoV-A material is more difficult to weld than nickel alloyed steels and it requires very high preheating to avoid hot cracking due to welding.

The Armenian RPV surveillance programme consists of 3 materials:

- base metal (BM),
- weld N4 located opposite to reactor core (Weld),
- heat affected zone (HAZ) with base and weld metals on either side.

The chemical compositions of Armenian surveillance specimens are shown in Table 1.

3. Surveillance specimens irradiation and thermal ageing conditions

The Armenian RPV surveillance programme consists of six specimen sets. The thermal aged specimens are included in two of these six sets. Each of these sets consists of 2 chains located at the corner of the hexagon active core. The specimens have been placed into stainless steel capsules. Each capsule includes either six tensile or two Charpy specimens. The standard surveillance capsule with Charpy specimens is shown in Fig. 1.

The thermal aged specimens are exposed to temperature ~290 °C because they are located above the core in front of the upper (outlet) nozzle ring. The lower part of the surveillance chain consists of capsules with specimens irradiated at 270 °C. The scheme of the chain location in reactor is shown in Fig. 2. It should be noted that the current paper focuses on the mechanical testing results of the thermal aged specimens taken from the last (6th) surveillance chain of Armenian NPP. The future research will focus on the testing of irradiated specimens from the same surveillance

Table 1
Chemical compositions of Armenian surveillance specimens (in weight %).

Steel	C	Mn	Si	Ni	Cr	Mo	V	Cu	P	S
BM	0.17	0.52	0.35	0.19	2.88	0.66	0.33	0.10	0.012	0.014
Weld	0.07	1.27	0.52	0.15	1.56	0.47	0.20	0,20	0,032	0021
HAZ	0.15	0.38	0.27	0.11	2.74	0.74	0.33	0.09	n/a	0.012