Investigation of VVER-440 RPV surveillance test specimens from Armenian NPP

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Abstract

The basic results of Armenian RPV surveillance are presented. 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. Mechanical testing and microstructural investigation on surveillance specimens were carried out after irradiation and after recovery annealing treatment. Annealing for 100h at 475°C recovered the tensile strength and relative uniform elongation by 82% and 97% respectively and caused the complete disappearance of the irradiation-caused black-dot damage.

Background

The Reactor Pressure Vessel is a key component of the Nuclear Power Plant (NPP). The integrity assessment of the RPV is one of the main issues for the safe and long term operation of NPPs. The primary mechanisms contributing to the degradation of RPV mechanical properties are neutron irradiation and thermal ageing 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.

As most of the existing NPPs are considering for extending their operation life, the thermal ageing and irradiation induced degradation of RPV steels becomes more significant for the extended periods of operation. In this respect, both thermal ageing and irradiation effects should be evaluated to perform structural integrity assessments for the lifetime extension of NPPs.

Experimental methods
Materials

The 440 MWe Water Water Energy Reactor (VVER-440) in Armenia was put into operation by the end of 1979. The VVER pressure vessel materials differ from the Western RPV steels. The chromium-molybdenum-vanadium steel grade 15Cr2MoV-A used for the VVER-440 pressure vessels contains ~0.3 weight 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 consisted of the following 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.

Table 1: Chemical compositions of Armenian surveillance specimens (in wt. %). Steel

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	0.021
HAZ	0.15	0.38	0.27	0.11	2.74	0.74	0.33	0.09	n/a	0.012

The standard surveillance capsule with Charpy specimens is shown in Figure 1.

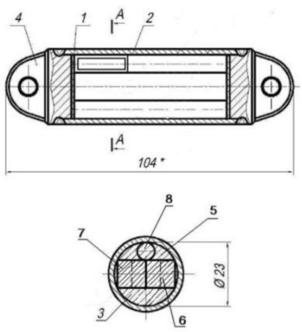

Figure 1. The standard capsule with surveillance specimens (1-packing; 2-vessel; 3-filler; 4- cover; 5-filler; 6&7-Charpy specimen; 8-neutron flux monitor).

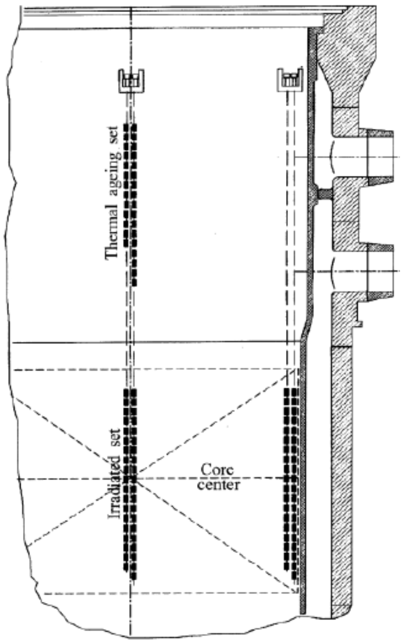

Figure 2. The location scheme of surveillance chains in VVER-440 reactor.

The thermal aged specimens were exposed to temperature of 290°C because they were located above the core in front of the upper (outlet) nozzle ring. The lower part of the surveillance chain consisted of capsules with specimens irradiated at 270°C. A scheme of the chain location in ANPP reactor is shown in Figure 2. It should be noted that here we presents the mechanical and microscopic results of specimens taken from the last (6th) surveillance chain of Armenian NPP.

Influence of long term thermal ageing

Tensile testing results of aged and as-received specimens at the room temperature are shown in Figure 3. The results show that there is no significant difference between the properties of as-received and aged weld metals. No age hardening has been detected in aged specimens compared with the as-received specimens. The aged weld specimens demonstrated similar plasticity as the as-received ones. This indicates the absence of thermal ageing effect for the 15Cr2MoV-A weld after ~200,000 hours of ageing at 290 °C.

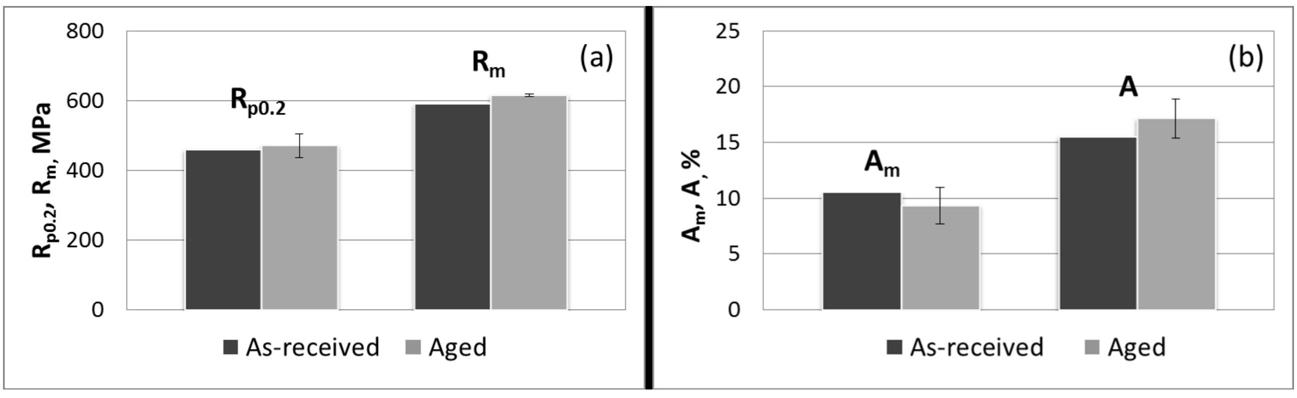

Figure 3. Tensile testing results of as-received and aged Armenian weld tested at room temperature: a) strength properties, b) ductility properties. Reported as-received data are obtained from Ref. [1].

The Charpy testing results of as-received and aged welds are shown in Figure 4. The results demonstrate that there is no significant difference between the impact properties of as-received and aged weld metals.

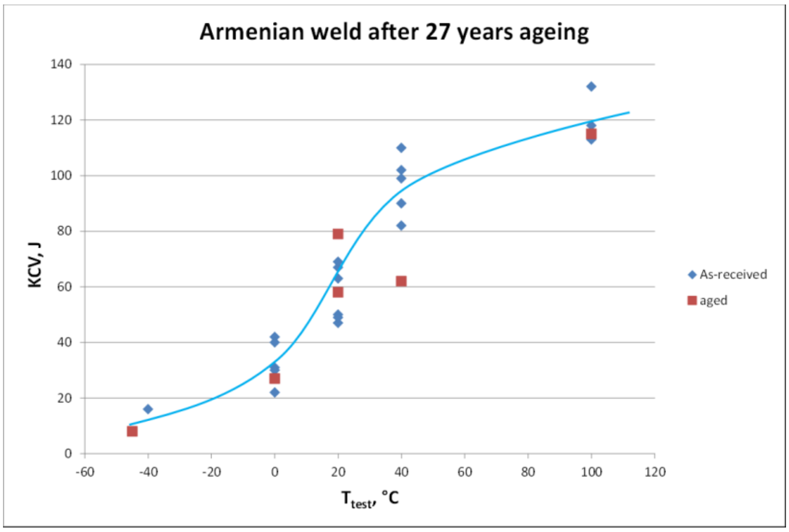

Figure 4. The Charpy testing results of as-received and thermal aged Armenian weld.

The Charpy testing results of as-received and thermal aged HAZ are shown in Figure 5.

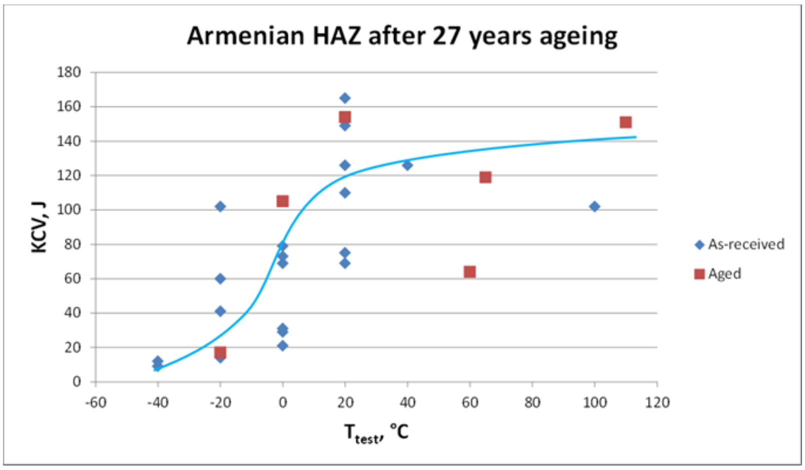

Figure 5. The Charpy testing results of as-received and thermal aged Armenian HAZ.

The mechanical testing and microstructural examination (Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM)) of thermal aged surveillance specimens of Armenian VVER-440 NPP, at ~290 °C for ~200,000 hours, were performed. Results of the tensile and impact tests indicated the absence of hardening and embrittlement of long term thermal aged 15Cr2MoV-A weld. It was found that the microstructure of thermal aged weld, consisting carbides, carbonitrides and manganese-silicon inclusions, did not change significantly compared to as-received state.

Influence of high fluence irradiation and effect of recovery annealing

Tensile testing was performed at room temperature on irradiated and irradiated and annealed VVER-440 weld surveillance specimen which have received extreme high beyond-design fluence values of $3.2{\cdot}10^{25}m^{-2}$ (E>0.5MeV). The yield strength ($R_{p0.2}$), ultimate tensile strength (R_m), relative total elongation (A) and relative uniform elongation (A_m) of the VVER-440 surveillance specimen can be viewed in Figure 6. These results include the data from as-received and thermally aged material to illustrate the level of recovery caused by the two different annealing treatments [2, 4].

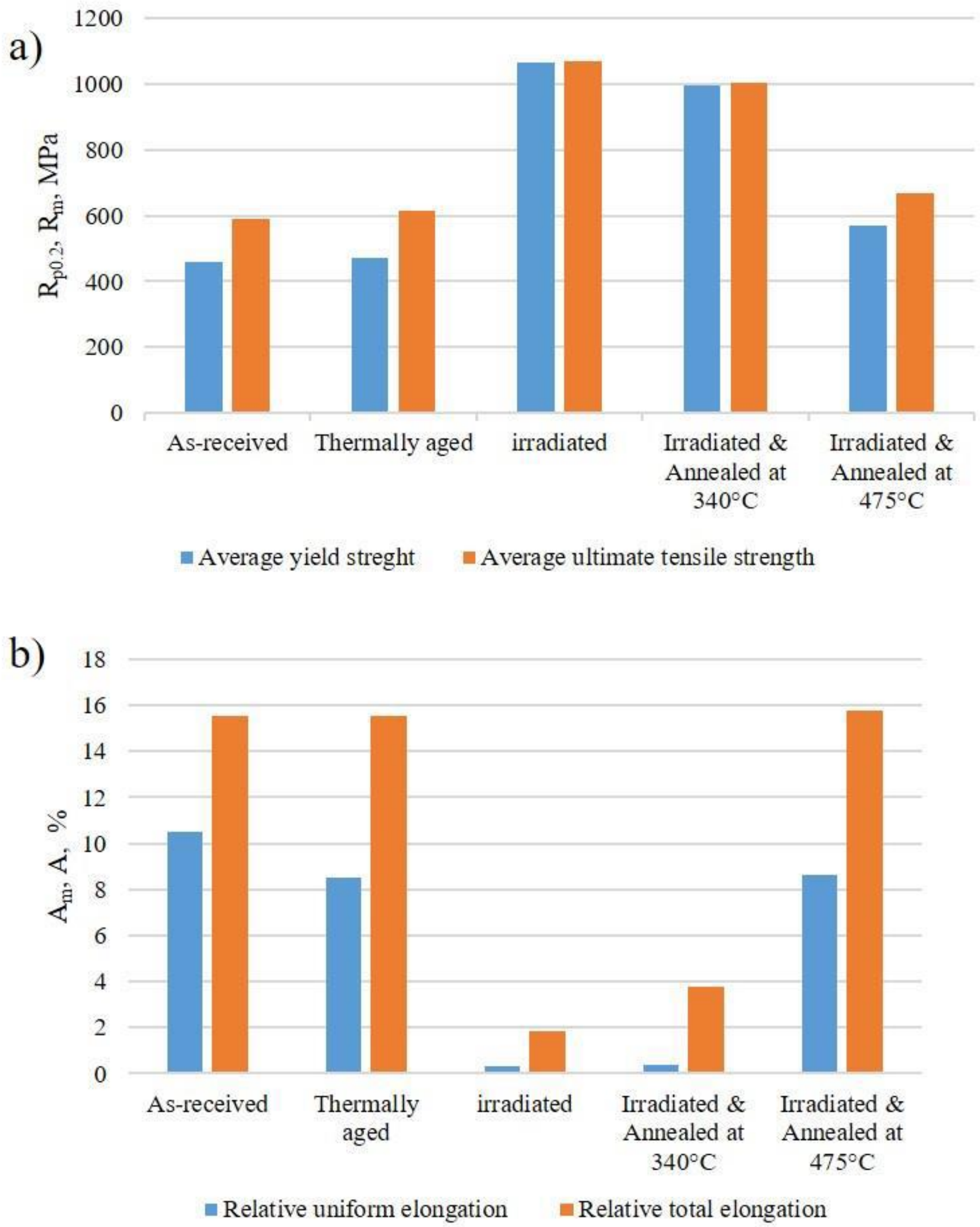

Figure 6: The tensile testing results of the irradiated and annealed VVER-440 weld Armenian surveillance specimen: a) strength properties, b) ductility properties. The tests were carried out at room temperature.

Table 2: Summary of the tensile testing results of the irradiated and annealed VVER-440 welds. The changes in $R_{p0.2}$ ($\Delta R_{p0.2}$) and A_m (ΔA_m) with respect to the as-received state and the recovery of $R_{p0.2}$ and A_m ($\Delta R_{p0.2,recovery}$, $\Delta A_{m,recovery}$) with respect to irradiated state after annealing are presented.

	Irradiated F= 2.3-4.2·$10^{25}$$m^{-2}$ (E≥ 0.5 MeV)	Irradiated & annealed for 100h at 340 °C	Irradiated & annealed for 100h at 475 °C
$\Delta R_{p0.2}$ [MPa]	606	535	101
ΔA_m [%]	10.2	10.1	1.85
$\Delta R_{p0.2,recovery}$ [MPa]	-	71 (12%)	496 (82%)
$\Delta A_{m,recovery}$ [%]	-	25	97

The above results demonstrate the effectiveness of thermal annealing at 475°C in significant recovery of the initial strength and ductility properties of VVER-440 RPV steels even after exposure to extremely high fluence values.

The microstructure of irradiated and irradiated & annealed weld metals was investigated with the use of TEM (Transmission Electron Microscopy). Prior to these investigations, the microstructure of as-received weld VVER-440 metal was studied. The detailed results of the reference microstructural investigation can be viewed in [2, 4].

Table 3: The results of the transmission electron microscopy analysis of 15Cr2MoV-A VVER-440 welds in as-received condition, irradiated (3.2·10^{25} m^{-2}, E≥ 0.5 Mev) and annealed for 100h at two different temperatures.

VVER-440 15Cr2MoV-A Weld				
Condition	N_{disks} x 10^{21} (m^{-3})	$<d>_{disks}$ (nm)	$N_{black-dot}$ x 10^{21} (m^{-3})	$<d>_{black-dot}$ (nm)
As-received	7-12	16-20	-	-
Irradiated F= 3.2 10^{25} m^{-2} (E≥ 0.5 MeV)	7-12	17	80-140	6-5
Irradiated & annealed for 100h at 340 °C	5-9	16-21	10-19	10-12
Irradiated & annealed for 100h at 475 °C	7-12	18-19	-	-

Thermal annealing at 475°C proved to be an effective method to recover the irradiation-induced hardening (Figure 7). Analysis of the TEM micrographs show that after thermal annealing treatment at 475°C, the number density of the precipitates in the welds are comparable to number density of the vanadium and molybdenum carbonitrides precipitates in the as-received non-irradiated weld suggesting the dissolution of the Cu back into the matrix.

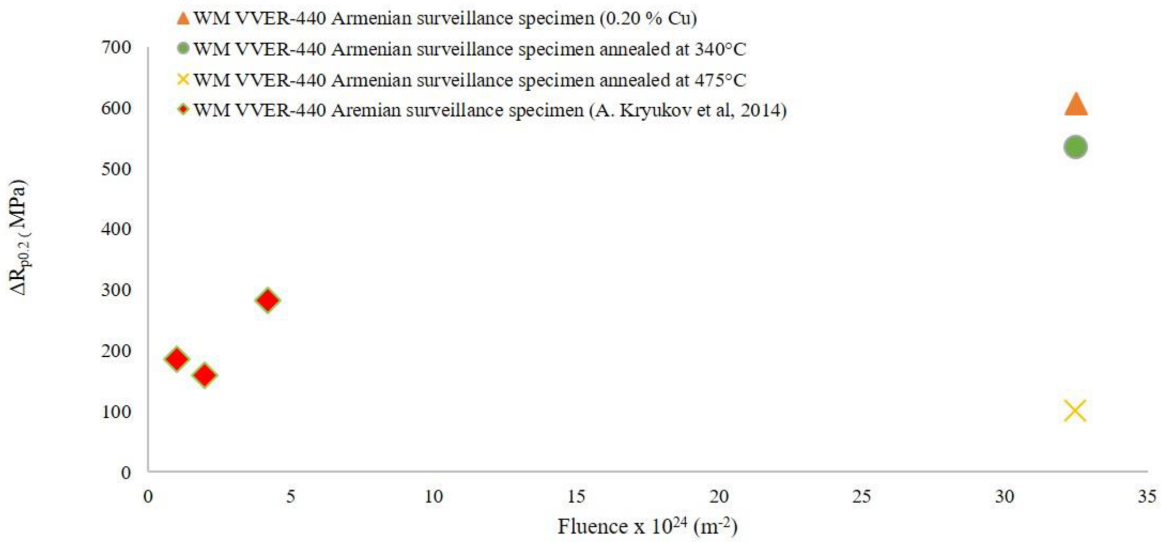

Figure 7: Comparative dose dependence of the change in yield strength in VVER-440 welds with respect to the as-received state. The data points for the Armenian surveillance specimen at lower fluence values and comparable fluence rate ($3.5\text{-}3.9 \cdot 10^{16} m^{-2} s^{-1}$) are published in [3].

Conclusion

Annealing for 100h at 475°C recovered the tensile strength and relative uniform elongation by 82% and 97% respectively and caused the complete disappearance of the irradiation-caused black-dot damage.

ANPP operational lifetime expired in 2016, and it has been extended for 10 years. We are going to prolong the lifetime of ANPP till 2036. Therefore, this issue is of great importance.

References

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