Evaluation of mechanical properties for heat affected zone in WWER-1000 RPVs based on surveillance test data

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Abstract: According to the surveillance program requirements in Ukraine a radiation embrittlement of RPV materials is being evaluated using surveillance test data for base and weld as well as heat affected zone metal. However, for the RPV integrity analysis the mechanical test results for base and weld metal are used only. In this study the analysis of mechanical properties for HAZ metal has been carried out in a view point of their application in the surveillance program. A transition temperature T_K for base and HAZ metal in unirradiated condition was considered. The radiation embrittlement rate for RPV materials was also evaluated. In addition a relation between the embrittlement and hardening rate has been estimated. The analysis has shown that in the most cases the initial T_K temperature for base metal is lower or comparable to that of HAZ metal. For all reactor pressure vessels considered the radiation embrittlement rate for HAZ metal is lower than for base and/or weld metal with the exception of one NPP unit. Furthermore, the comparison between the tensile and Charpy impact test data has shown there is an unusual high embrittlement of HAZ metal for one reactor pressure vessel that does not comply with the radiation hardening rate.

INTRODUCTION

In Ukraine there are thirteen NPP units with WWER-1000 reactor pressure vessel under operation. According to the PNAE G-7-008-89 regulatory requirements [1] a periodical inspection of RPV metal condition should be performed using non-destructive and destructive examinations during a RPV service life. One of the main topics of the periodical inspections is an evaluation of RPV metal degradation due to the operation factors (neutron irradiation, coolant temperature, etc.). The radiation embrittlement is considered as a key phenomenon in the RPV material degradation. To estimate the radiation embrittlement effect the surveillance program is fulfilled for the specific nuclear power plant. The specimens made of base, weld and heat affected zone metal are included in nomenclature of the surveillance specimens. For base and weld metal the tension, Charpy impact and fracture toughness specimens are used to estimate the changes in the mechanical properties of RPV materials (yield strength increase, transition temperature and fracture toughness curve shift due to irradiation, etc). In the case of HAZ metal the Charpy V-notch and fracture toughness specimens are applied only.

In order to estimate the radiation embrittlement rate for RPV materials the regulatory guide PNAE G-7-002-86 [2] requires to use the Charpy impact test data. However, an experience has shown that HAZ metal in unirradiated and irradiated condition reveals a high scatter in the test data for Charpy curve. It is related to a position of V-notch on the Charpy specimen. This issue does not allow to determinate the radiation shift of transition temperature reliably. So the Charpy impact test data for HAZ metal is not considered in the analysis of RPV material embrittlement. Nevertheless in this paper the surveillance test data for HAZ metal has been analyzed in view point of radiation hardening and embrittlement in comparison to base and weld metal. For the analysis the tensile and Charpy impact test results have been used for nine WWER-1000 reactor pressure vessels for which the HAZ surveillance test data are available.

MATERIALS AND ANALYSIS METHODS

The RPV materials (base, weld and HAZ metal) for nine NPP units with WWER-1000 type reactor were included in the analysis. The core shells for these reactor pressure vessels are fabricated using low carbon low alloyed ferritic steel (15Kh2NMFA-A grade, a pure burden) with exception of RPV lower shell for unit Y (15Kh2NMFA grade, an ordinary burden). The chemical composition for base and weld metal is shown in Table 1. The typical heat treatment for base metal of core shells is quenching with high tempering. For welds the high tempering is applied. The yield strength of RPV materials in unirradiated condition is within 539 – 641 MPa and 437 – 630 MPa for base and weld metal respectively.

Specimens were irradiated in the standard surveillance capsules up to the neutron (E > 0,5 MeV) fluence of $68{,}7 \cdot 10^{22}$ m^{-2}. Irradiation temperature was about 300°C. The surveillance specimens were irradiated by neutron flux of about 10^{15} m^{-2}/sec that is usual for WWER-1000 type reactor irradiation condition. The tensile and Charpy impact test data have been used for the analysis. The tensile test data for base metal is applied for HAZ metal as well.

Table I. Chemical composition for base and weld metal – key alloying elements and impurities

NPP unit	Material	Element (% wt)			
		Mn	Ni	Cu	P
		Base metal			
K	15Kh2NMFA-A	0,46	1,26	0,1	0,01
L	15Kh2NMFA-A	0,46	1,17	0,05	0,008
M	15Kh2NMFA-A	0,38	1,12	0,05	0,01
N	15Kh2NMFA-A	0,47	1,2	0,09	0,01
R	15Kh2NMFA-A	0,35	1,12	0,05	0,008
P	15Kh2NMFA-A	0,43	1,1	0,05	0,007
Q	15Kh2NMFA-A	0,48	1,12	0,06	0,007
W	15Kh2NMFA-A	0,54	1,23	0,05	0,008
Y	15Kh2NMFA	0,44	1,19	0,12	0,01
		Weld metal			
K	Sv-12Kh2N2MAA, flux ФЦ-16	0,74	1,67	0,04	0,006
L	Sv-10KhGNMAA, flux ФЦ-16	0,94	1,7	0,04	0,007
M	Sv-10KhGNMAA, flux ФЦ-16	0,76	1,64	0,03	0,008
N	Sv-12Kh2N2MAA, flux ФЦ-16	0,82	1,38	0,04	0,006
R	Sv-12Kh2N2MAA, flux ФЦ-16	0,74	1,72	0,06	0,005
P	Sv-12Kh2N2MAA, flux ФЦ-16	0,67	1,55	0,03	0,008
Q	Sv-10KhGNMAA, flux ФЦ-16	0,97	1,88	0,02	0,006
W	Sv-08KhGNMTA, flux 48-НФ-18М	1,00	1,12	0,04	0,009
Y	Sv-10KhGNMAA, flux ФЦ-16	0,93	1,74	0,05	0,007

The standard Charpy specimens (10 x 10 x 55 mm) were used for the estimation of impact energy in the specified temperature range. For this purpose an impact pendulum machine (C-type pendulum) with 300 Joules capacity and the environment chamber were applied to get the Charpy curves for unirradiated and irradiated materials. A shift of transition temperature due to irradiation is defined according to PNAE G-7-002-86 approach (an index temperature for the Charpy curve depends on the material yield strength). The Charpy V-notch specimens for HAZ metal were with T-S orientation. A position of HAZ specimens relative to RPV weld is shown in fig. 1. The round specimens with a reduced diameter of 3 mm and a gauge length of 30 mm are used to evaluate the changes in material strength properties due to neutron irradiation.

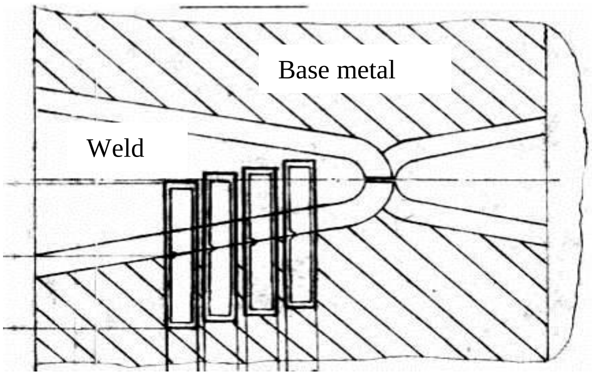

Fig. 1 Position of HAZ specimens relative to welds

The radiation embrittlement rate for RPV materials has been estimated using the fluence dependencies of Charpy impact curve shift (ΔT_F). The PNAE G-7-002-86 embrittlement model $\Delta T_F = A_F \cdot F^n$ (where F is neutron fluence in the terms of 10^{22} m^{-2} and a power exponent n = 1/3) is applied to define a chemistry factor A_F using a statistical analysis. The similar model of radiation hardening ($\Delta R_{p0,2} = B_F \cdot F^n$) is applied to estimate the radiation hardening coefficient B_F.

TEST RESULTS AND DISCUSSION

In order to compare the impact toughness of RPV materials the Charpy impact test data have been analyzed. The transition temperatures T_{KI} for HAZ and base metal in unirradiated condition are shown in fig. 2. In the most cases the initial T_{KI} temperature for base metal is lower or comparable to that of HAZ metal. However for some of reactor pressure vessels the T_{KI} temperature of base metal in unirradiated condition is higher in comparison to HAZ metal.

The radiation embrittlement rate obtained from surveillance test data for HAZ relative to base and weld metal is represented in fig. 3 where the ratio of A_F coefficients (chemistry factor) for RPV materials (i.e. $\frac{A_F^{HAZ}}{A_F^{Base}}$ and $\frac{A_F^{HAZ}}{A_F^{Weld}}$) is used. The analysis has shown that for all reactor pressure vessels considered the radiation embrittlement rate for HAZ metal is lower than for base and/or weld metal with the exception of unit Y. For Y unit reactor pressure vessel the susceptibility of HAZ metal to neutron irradiation is higher in comparison to base and weld metal. This outcome is most probably related to a comparatively high content of copper (0,12 % wt) and phosphorus (0,01 % wt) in the unit Y lower shell which is fabricated of 15Kh2NMFA grade steel smelted on the ordinary burden. Furthermore, the embrittlement rate of HAZ metal for a unit W reactor pressure vessel is higher in comparison to weld metal that is also unusual for RPV materials considered (see fig. 3).

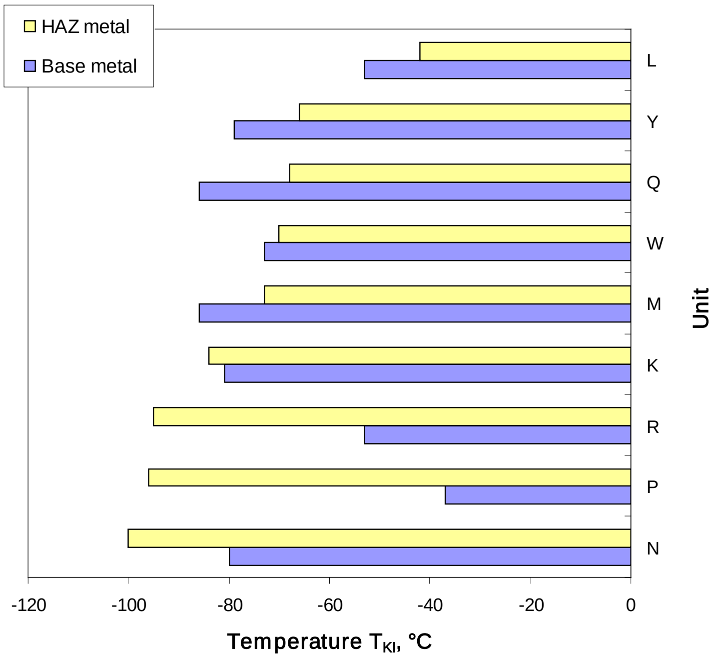

Fig. 2 Transition temperature T_{KI} for HAZ and base metal in unirradiated condition

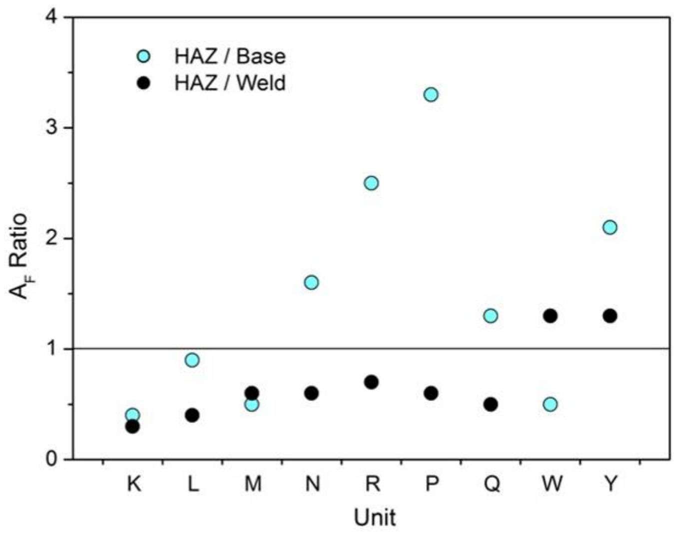

Fig. 3 Radiation embrittlement rate for HAZ relative to base and weld metal

In this paper the additional analysis of tensile and Charpy impact test data has been performed for HAZ and base metal. The B_F and A_F coefficients have been applied to evaluate the increase of yield strength and the transition temperature shift respectively according to relationships from the PNAE G-7-002-86 regulatory guide. The correlation of radiation hardening to embrittlement for HAZ and base metal is shown in fig. 4.

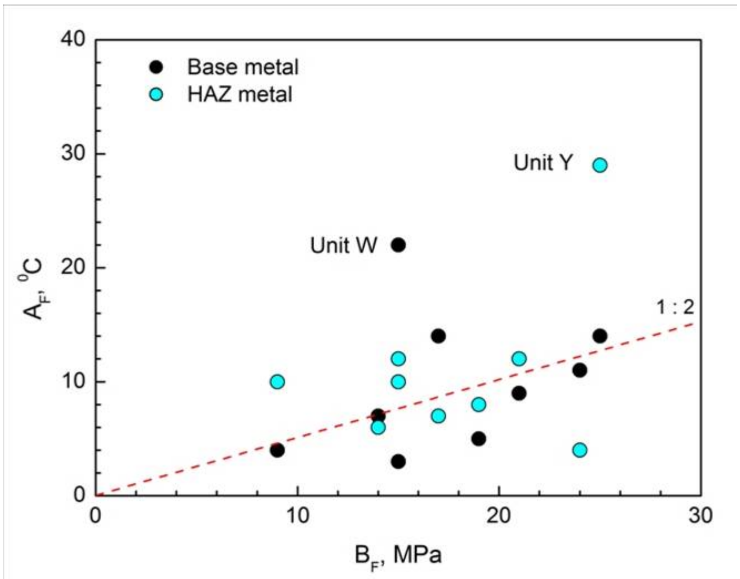

Fig. 4 Radiation hardening (B_F) to embrittlement (A_F) correlation for HAZ and base metal

The analysis has shown the relation between the yield strength increase and transition temperature shift due to irradiation for RPV materials results in a factor of 0,6 in average. This outcome is close to a known empirical correlation $\Delta T_{41J} = 0,7 \cdot \Delta R_{p0.2}$ for pressure vessel steels [3]. However, for the unit Y heat affected zone metal the high embrittlement rate is not consistent with radiation hardening considering the abovementioned correlation that can be associated with additional radiation damage mechanisms. The similar discrepancy is also observed for the unit W base metal.

CONCLUSIONS

The surveillance test data for HAZ metal has been analyzed in view point of radiation hardening and embrittlement in comparison to base and weld metal. For the analysis the tensile and Charpy impact test results have been used for nine WWER-1000 reactor pressure vessels. The conclusions can be drawn as follows:

- in the most cases the initial T_{KI} temperature for base metal is lower or comparable to that of HAZ metal. However, for some of reactor pressure vessels the T_{KI} temperature of unirradiated base metal is higher in comparison to HAZ metal;
- for all reactor pressure vessels considered the radiation embrittlement rate for HAZ metal is lower than for base and/or weld metal with the exception of one NPP unit that most probably related to comparatively high content of copper and phosphorus in the RPV shell;
- there is an unusual high embrittlement of HAZ metal for one WWER-1000 RPV that does not comply with the radiation hardening rate considering the known empirical correlation.

REFERENCES

1. PNAE G-7-008-89 Rules for Design and Safe Operation of Components and Piping of NPPs, Moscow: Energoatomizdat, 1990
2. PNAE G-7-002-86 Strength Calculation Norm for Nuclear Power Plant Equipment and Piping. Moscow: Energoatomizdat, 1989, 525 p
3. Odette G.R., Lombrozo P.M., Wullaert R.A. Relationship between Irradiation Hardening and Embrittlement of Pressure Vessel Steels / Effects of Radiation on Materials (12th Int. Symp.), ASTM STP 870, Philadelphia, PA (1985) 840–860