Re-embrittlement of WWER-440 Reactor Pressure Vessel Weld Material

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At present validation of lifetime extension behind 45 years for operating of Nuclear Power Plant units with WWER-440 first generation type reactors is one of the considering strategic directions of works in the development of nuclear power engineering in Russia for the years ahead. The problem of lifetime extension of WWER-440 first generation was solved by weakening of radiation embrittlement of reactor pressure vessel (RPV) welds that are located opposite to the core by annealing at definite temperature-time processing modes.

Absence of surveillance programs and performed annealing caused the necessity of predictive evaluations for WWER-440 RPV materials.

The results of nanostructure investigations [1] and mechanical properties testing have shown that there is no necessity of taking into account flux effect for re-embrittlement assessment of WWER-440 materials [1-4]. Method of accelerated re-irradiation of specimens at fluxes considerably higher than on reactor pressure vessel wall was used to obtain the long-term prediction for radiation dose corresponding to the design life time of RPV and beyond. Two types of materials for re-irradiation were used for that purpose: templets taken from inner surface of RPVs after annealing and research specimens which were irradiated by high neutron flux and then annealed.

The analysis of the data on re-irradiation embrittlement of WWER-440 reactor pressure vessel weld materials obtained after low dose rate irradiation as a part of operating RPV wall (templets) and after accelerating radiation have shown a big difference in re-irradiation behavior between them.

It was found that the rate of re-irradiation depends of radiation pre-history (fast neutron dose rate) of the material.

Investigations which have been carried out made a possibility to assume that WWER-440 RPV weld metal after irradiation and annealing can be considered as a "NEW MATERIAL". It confirms by following results:

1) Rate of primary irradiation embrittlement remarkable differ from re-irradiation rate for WWER-440 RPV weld materials
2) Yield stresses in as receive condition and after irradiation and annealing condition are considerably differ
3) Microstructures of the material after irradiation and annealing and in as receive condition are considerably differ

The value of transition temperature after post irradiation annealing (T_{ka}) could be a parameter characterizing material condition after irradiation and annealing.

The comparative analysis and comparison of the atom-probe tomography microscopy data of research samples after accelerating radiation with the results of templates samples studying have shown a difference of nanostructure for these materials in irradiated, annealed and re-irradiated conditions [6]. Main conclusions from the analysis of nanostructure are shown in Table 1.

Table 1.

<table>
<tr><th>Research programs
(accelerated primary irradiation)</th><th>Templets
(not accelerated primary irradiation)</th></tr>
<tr><td>Occurring of Cu-P clusters with Cu – content (~10 at. %) at primary irradiation – Easer to dissolved under re-irradiation</td><td>Occurring of Cu-P clusters with Cu – content (~20 at. %) at primary irradiation</td></tr>
<tr><td>Bigger amount of Cu is returning to a matrix at annealing</td><td>Smaller amount of Cu is returning to a matrix at annealing</td></tr>
<tr><td colspan="2">The more clusters it was dissolved - the less value of T_{ka} and the more new Cu-clusters occurred under re-irradiation.
T_{ka} – is a parameter responsible for characterization of materials capability for occurring of new Cu – enriched precipitates under re-irradiation
$T_{ка}$ – is a parameter which is characterizing level of hardening of the material after irradiation and annealing</td></tr>
<tr><td>Occurring of P-enriched zones</td><td>Occurring of P-enriched zones</td></tr>
<tr><td colspan="2">P influences to kinetics of re-irradiation by occurring of precipitates on the base of P</td></tr>
</table>

The model of transition temperature shift evaluation under re-irradiation for WWER-440 RPV weld materials with T_{ka} value as a parameter was proposed (1).

$$T_k^{re\text{-}irr} = T_{ka} + 646 \times (P - 0{,}02) \times e^{(1 - 0{,}01 \times T_{ka})} \times \Delta F^{0.36} + 2\sigma, \quad (\sigma = 17{,}2°C) \tag{1}$$

Comparison of experimental and calculated by equation (1) results is shown on figure 1.

It is clear that elaborated model (1) is adequate and conservative for common database consist of templets and research specimens investigation results.

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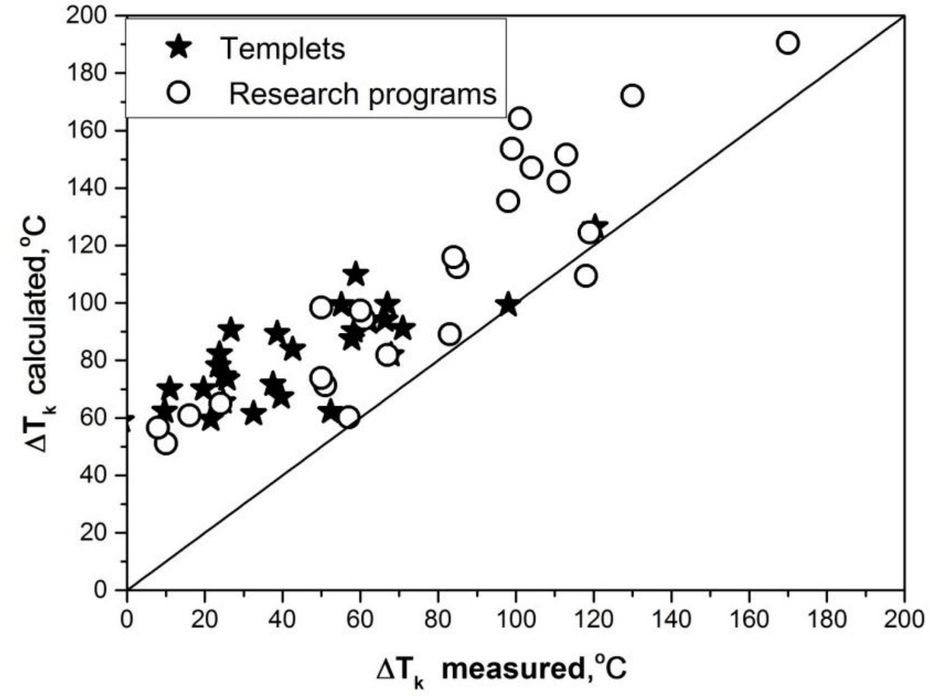

Figure 1. Comparison of experimental and calculated by equation (1) results for materials from research programs (open circles) and templets (filled stars).