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The Use of Master Curve Method for Statistical Re-Evaluation of Surveillance Test Data for WWER-1000 Reactor Pressure Vessels

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Використання методу Master Curve для статистичної переоцінки даних випробувань зразків-свідків для корпусів реакторів ВВЕР-1000

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Дані випробувань на в'язкість руйнування зразків-свідків корпусних матеріалів реакторів ВВЕР-1000 АЕС України було переоцінено за допомогою методу Master Curve. Показано, що експериментальна температурна залежність параметрів в'язкості руйнування і розкид значень K_{Jc} *для матеріалів у неопроміненому стані та після опромінення флюенсом 41,* $2 \cdot 10^{22}$ *нейтр/м*^{2} *(*$E > 0{,}5$ *МеВ) добре узгоджуються з формою Master Curve, 5- і 95%-ними довірчими межами. Аналіз даних для корпусу реактора блока № 1 Хмельницької АЕС свідчить, що при використанні нормативного підходу ПНАЕ Г-7-002-86 суттєво недооцінюється визначена в'язкість руйнування зварного шва в неопроміненому стані. Температуру* T_0*, що визначена за методом Master Curve, порівнювали з критичною температурою крихкості* T_{K0} *для корпусних матеріалів у неопроміненому стані. Установлено, що температура* T_0 *значно нижча за* T_{K0}*. Окрім того, різниця у значеннях* T_0 *і* T_{K0} *для матеріалів суттєва. Побудовано кореляційну залежність для температур* T_{28J}*, що визначені за результатами випробувань стандартних зразків Шарпі, та* T_0*, отриманих при випробуваннях зразків Шарпі з тріщиною на в'язкість руйнування. Аналіз показав, що результати випробувань зразків Шарпі з тріщиною втоми можуть давати неконсервативну оцінку в'язкості руйнування матеріалів корпусів реакторів ВВЕР-1000.*

Ключові слова: реактор ВВЕР-1000, корпусні сталі, зразки-свідки, критична температура крихкості, зразки Шарпі, в'язкість руйнування, метод Master Curve.

Introduction. An estimation of reactor pressure vessel (RPV) steel fracture toughness is based on the Charpy impact test data according to a normative method adopted in Ukraine [1]. The normative approach estimates fracture toughness in the indirect way. An application of the Master curve methodology allows one to determine directly the RPV materials fracture toughness. According to Wallin's investigations [2], the normative approach results in the highly conservative fracture toughness estimation for Western RPV steels. Furthermore, an analysis of the ASME database has shown that application of Master curve method improves essentially the material fracture toughness estimation [3].

However, for comprehensive use of the Master Curve method, several scientific and technical issues should be solved. One of them is precise determination of fracture toughness parameters when testing such small specimens as precracked Charpy V-notch (PCVN) ones. This is a critical issue since PCVN specimens are inserted into the surveillance capsules for Ukrainian nuclear power plants (NPP).

The aim of present work was to re-evaluate the surveillance fracture toughness test data for Ukrainian NPPs using the Master curve method and compare the normative (PNAÉ G-7-002-86) with new statistical approaches in viewpoint of material fracture toughness characterization.

Material and Specimens. The WWER-1000 type RPV steels (15Cr2NiMoVAA grade) and their welds are included in the current analysis. The content of key alloying elements and detrimental impurities in RPV materials is presented in Table 1. These materials are extremely pure with regard to copper and phosphorus. At the same time welds have high nickel and manganese content which increases their susceptibility to neutron irradiation in spite of low Cu and P contents. Weld metal for the Khmelnitsky NPP unit 1 (KhNPP-1) has the highest Ni and Mn content.

T a b l e 1

Key Alloying Elements and Detrimental Impurities Content in RPV Materials

Unit	Chemical element, wt.%							
	Ni	Mn	Cu	P	Ni	Mn	Cu	P
	Base metal				Weld metal			
KhNPP-1	1.12	0.48	0.06	0.007	1.88	0.97	0.02	0.006
SUNPP-1	1.17	0.46	0.05	0.008	1.70	0.94	0.04	0.007
SUNPP-2	1.19	0.44	0.12	0.016	1.74	0.93	0.05	0.012
SUNPP-3	1.12	0.35	0.05	0.008	1.72	0.74	0.06	0.005
ZaNPP-1	1.20	0.48	0.08	0.007	1.10	0.78	0.03	0.005
ZaNPP-3	1.10	0.43	0.05	0.007	1.55	0.67	0.05	0.007

The experimental data used for the analysis were obtained from surveillance tests for six Ukrainian RPVs: KhNPP-1, three units of South-Ukrainian (SUNPP-1, SUNPP-2, and SUNPP-3) and two units of Zaporizhzhya nuclear power plant (ZaNPP-1 and ZaNPP-3).

The fracture toughness data obtained from precracked Charpy specimen tests were used for the statistical re-evaluation. The Charpy impact test data were used to determine temperature indices corresponding to the absorbed energy level of 28 J [4].

Surveillance specimens were irradiated by flux of about 10^{15} n/(m$^2 \cdot$s) that is usual for WWER-1000 type reactor irradiation condition. The fast neutron ($E > 0.5$ MeV) fluence for specimens was 4.2 to $41.2 \cdot 10^{22}$ n/m^2. Irradiation temperature is about 300°C. Thermal ageing time was 3813 effective days for thermally aged specimens.

Statistical Re-Evaluation Procedure. The available fracture toughness data were analyzed and a censoring procedure according to the ASTM E 1921-97 standard deformation criterion [4] was applied for invalid K_{Jc} values. Then results for 0.4T specimen thickness were converted to their 1T equivalents using a thickness correction ratio:

$$K_{Jc(1\mathrm{T})} = K_{\min} + (K_{Jc(0.4\mathrm{T})} - K_{\min}) \left(\frac{B_{0.4\mathrm{T}}}{B_{1\mathrm{T}}} \right)^{1/4}, \qquad (1)$$

where $K_{\min}$ is the lower bound fracture toughness, which for ferritic steel is equal to 20 $\mathrm{MPa} \cdot \mathrm{m}^{1/2}$.

After thickness correction the reference temperatures, T_0, were calculated using a maximum likelihood method and solving numerically the equation [5]:

$$\sum_{i=1}^{n} \frac{\delta_i \exp[0.019(T_i - T_0)]}{11 + 77 \exp[0.019(T_i - T_0)]} - \sum_{i=1}^{n} \frac{(K_{Jc}^{i} - 20)^4 \exp[0.019(T_i - T_0)]}{\{11 + 77 \exp[0.019(T_i - T_0)]\}^5} = 0, \qquad (2)$$

where $\delta_i = 1$ when K_{Jc} value is valid and $\delta_i = 0$ when K_{Jc} value does not meet the ASTM E 1921 standard deformation criterion with $M = 30$. Finally, the Master curves, 5 and 95% tolerance bounds for materials were obtained.

Fracture Toughness Test Results for the SUNPP-1. Surveillance test data for SUNPP-1 were re-evaluated using the Master curve approach. In this analysis, three irradiated sets and one thermally aged set are considered. Surveillance specimens from the 1st and 2nd withdrawals were tested at the Russian Research Centre Kurchatov Institute. Testing of surveillance specimens from the 3rd withdrawal was performed at the Institute for Nuclear Research of the National Academy of Sciences of Ukraine. The results of re-evaluation are shown in Figs. 1 and 2, where the fracture toughness data are presented in normalized temperature coordinates. The Master curves, 5 and 95% tolerance bounds for materials are drawn together with the experimental K_{Jc} values. As seen, the temperature dependencies of fracture toughness parameters and the statistical scatter of K_{Jc} values for WWER-1000 RPV steels are in a good agreement with the Master curve and 95% tolerance bounds.

The Comparison of Normative and Master Curve Approaches. In earlier investigations [6], it was found that the radiation embrittlement rate of KhNPP-1 RPV weld metal is higher than the design one. The main reason is the high Ni and Mn content in the material. It means this weld may limit the RPV design life or prevent the NPP service life extension. On the other hand, it is known that the normative approach estimates very conservatively the western RPV steel fracture toughness in some cases [3], and the application of the Master curve methodology allows us to improve the estimation of unirradiated RPV material fracture toughness.

Taking into account the above-mentioned issues we have compared the normative PNAÉ G-7-002-86 and statistical Master curve approach in viewpoint of the fracture toughness assessment for KhNPP-1 weld metal. At first, the normative

K_{Ic} curve was indexed by the critical brittleness temperature, T_{K0}, obtained from Charpy impact tests only. The design K_{Ic} curve for WWER-1000 type RPV welds has a form $[K_{Ic}]_3 = 35 + 53\exp[0.0217(T - T_{K0})]$. Temperature T_{K0} was determined by the manufacturer of the pressure vessel at the time of RPV material certification.

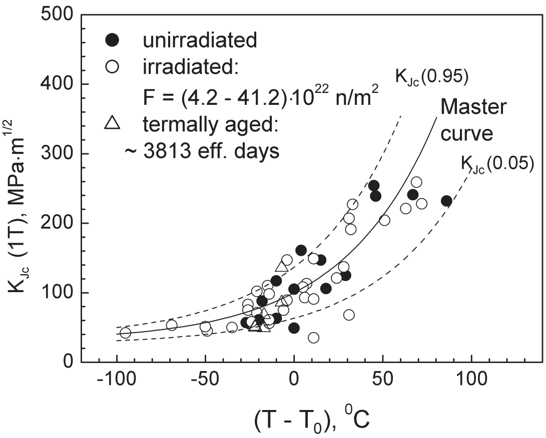

Fig. 1. Master curve for base metal (SUNPP-1).

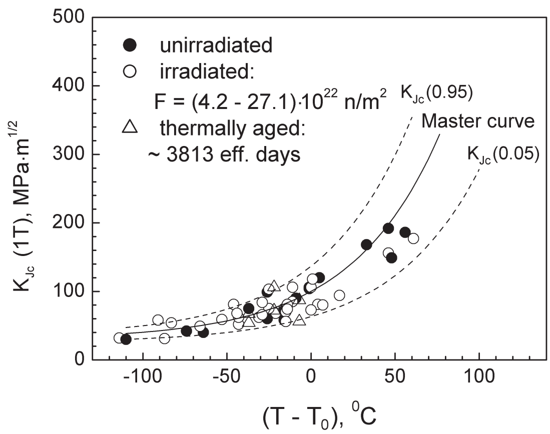

Fig. 2. Master curve for weld metal (SUNPP-1).

After the statistical re-evaluation a 5% Master curve tolerance bound that has a form $K_{Jc(0.05)} = 25.4 + 37.8\exp[0.019(T - T_0)]$ and the reference temperature, T_0, were obtained. A margin was added to cover the uncertainty in T_0 that is associated with the use of a small number of specimens to determine temperature T_0. Both curves were compared with the thickness-corrected K_{Jc} values based on the precracked Charpy specimens test data. It is noteworthy that the 5% Master curve tolerance bound and design K_{Ic} curve have almost the same shape.

The results of comparison are shown in Fig. 3. As seen, the normative approach underestimates essentially the measured fracture toughness in comparison with the Master curve. A shift between curves is about 50°C. Obviously the use of highly conservative data for the RPV integrity assessment may result in unnecessary limitations of the operational conditions and service life of the reactor pressure vessel. In this case, an application of the Master curve and temperature T_0 calculated from fracture mechanics test data allows one to solve this problem.

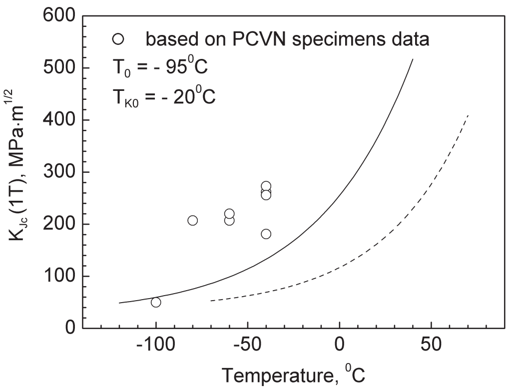

Fig. 3. Comparison of 5% Master curve tolerance bound (solid line) with normative K_{Ic} curve (dashed line) in regard to the measured fracture toughness parameters.

The Comparison of Measured Values of T_{K0} and T_0. The T_{K0} and T_0 values are used as temperature indices for the fracture toughness curves. In other words, these temperatures locate a K_{Ic} curve on the temperature axis. In order to understand to what extent these temperatures correspond to each other, a comparison of measured values of T_{K0} and T_0 was made. Figures 4 and 5 demonstrate the result of the comparison. We can see that temperature T_0 is much lower than T_{K0} in the most cases. Furthermore, a difference between T_0 and T_{K0} values varies essentially from one material to another.

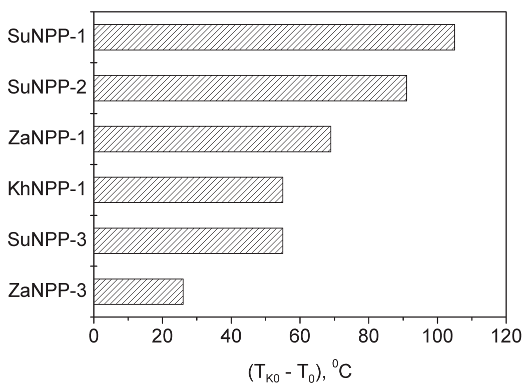

Fig. 4. Comparison of T_{K0} and T_0 temperatures for the unirradiated base metal.

Obviously a conservatism level defined according to the normative approach also varies considerably from one material to another. Therefore the temperature T_{K0} is not appropriate as an indexing parameter for the K_{Ic} curve. Unlike the normative approach, the Master curve method allows one to establish the same conservatism level for different RPV materials.

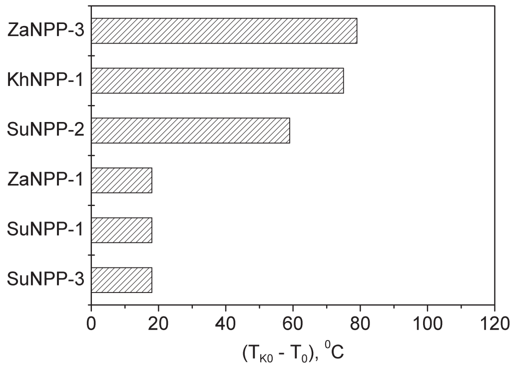

Fig. 5. Comparison of T_{K0} and T_0 temperatures for the unirradiated weld metal.

The Correlation between T_{28J} and T_0 Temperatures. According to Wallin's results [7], the correlation for RPV steels between T_{28J} and T_0 values has the form $T_0 = T_{28J} - 18°C$ (standard deviation is 15°C). The temperature T_{28J} is the transition temperature corresponding to Charpy impact energy of 28 J. The fracture toughness data used to determine the correlation were based on the 25 mm thickness specimen testing.

At present work we have analyzed a relationship between T_{28J} temperatures defined from the Charpy energy curves and T_0 values calculated from the precracked Charpy specimen tests. Both the unirradiated and irradiated up to fluence $\sim 41 \cdot 10^{22}$ n/m^2 specimens were chosen for the analysis. The correlation obtained is presented in Fig. 6. Results of the analysis have shown that such a correlation has the form $T_0 = T_{28J} - 40°C$ (standard deviation is 20°C). It means that T_0 values based on precracked Charpy specimen test data tend to be nonconservative, in comparison with T_0 values obtained from larger standard fracture mechanics specimens (bias is about 20°C). Certainly this is indirect evidence. In further investigations it would be necessary to perform fracture mechanics tests of specimens of different sizes and geometry and to estimate in the direct way a bias for T_0 related to the use of PCVN specimen data for the WWER-1000 RPV steel fracture toughness characterization.

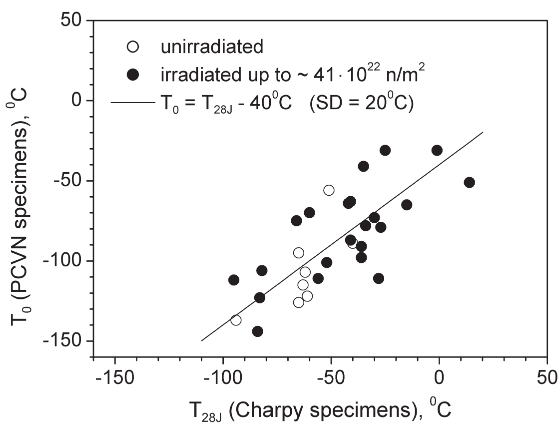

Fig. 6. Correlation between temperatures T_{28J} and T_0.

The fact that PCVN specimen test data may underestimate actual material fracture toughness can be explained by the constraint (crack-front triaxiality) loss effect. Based on the stochastic simulation it was found [8] that if constraint loss occurs at PCVN specimen testing the derived T_0 has a lower value than that determined for a data set of fracture toughness values measured under full constraint conditions (small-scale yielding conditions). Thus, the T_0 shift due to constraint loss occurs in only one direction (reducing the T_0 temperature). For a relatively tough and moderate strain-hardening materials the decrease in T_0 due to constraint loss effect may amount to $20°C$ when the E 1921 deformation limit M is equal to 30 [8].

Conclusions. The surveillance fracture toughness test data for WWER-1000 reactor pressure vessel materials from Ukrainian NPPs were re-evaluated using the Master curve methodology. The fracture toughness data were obtained from precracked Charpy specimens testing. Moreover, the Master curve approach was compared to a normative PNAÉ G-7-002-86 method, in viewpoint of adequate estimation of RPV steel fracture toughness. Results of analysis allow us to make the following conclusions.

1. The Master curve, 5 and 95% tolerance bounds describe adequately the temperature dependence of fracture toughness parameters and the statistical scatter of K_{Jc} values for WWER-1000 RPV steels both in unirradiated condition and after irradiation up to neutron fluence $41 \cdot 10^{22}$ n/m^2 ($E > 0.5$ MeV).

2. The normative approach estimates highly conservatively the unirradiated weld metal fracture toughness for Khmelnitsky NPP unit 1, in comparison with the Master curve method. A shift between the design K_{Ic} curve and 5% Master curve tolerance bound is about $50°C$. The application of the initial critical brittleness temperature, T_{K0}, to the assessment of reactor pressure vessel integrity may unnecessarily limit the operational conditions and service life of the Khmelnitsky NPP.

3. Precracked Charpy specimen test data may result in the nonconservative estimation of fracture toughness for WWER-1000 type RPV materials (bias is about $20°C$). This conclusion has been made in the indirect way. Therefore it is necessary to perform the additional tests of specimens with different geometry and directly estimate a bias for T_0 related to the use of PCVN specimen data for the RPV steel fracture toughness characterization.

Резюме

Данные испытаний на вязкость разрушения образцов-свидетелей корпусных материалов реакторов ВВЭР-1000 АЭС Украины были переоценены с использованием метода Master Curve. Показано, что экспериментальная температурная зависимость параметров вязкости разрушения и разброс значений K_{Jc} для материалов в необлученном состоянии и после облучения флюенсом $41{,}2 \cdot 10^{22}$ нейтр/м^2 ($E > 0{,}5$ МэВ) хорошо согласуются с формой Master Curve, 5- и 95%-ными доверительными границами. Анализ данных для корпуса реактора блока № 1 Хмельницкой АЭС свидетельствует, что при использовании нормативного подхода ПНАЭ Г-7-002-86 существенно недооценивается измеренная вязкость разрушения сварного шва в необлученном состоянии. Температуру T_0, определенную согласно методу Master Curve, сравнивали с критической температурой хрупкости T_{K0} для корпусных материалов в необлученном состоянии. Установлено, что температура T_0 намного ниже T_{K0}. Кроме того, различие в значениях T_0 и T_{K0} для материалов существенно разное. Построена корреляционная зависимость для температур $T_{28\,\mathrm{J}}$, определенных по результатам испытаний стандартных образцов Шарпи, и T_0, полученных при испытаниях образцов Шарпи с трещиной на вязкость разрушения. Анализ показал, что результаты испытаний образцов Шарпи с усталостной трещиной могут давать неконсервативную оценку вязкости разрушения материалов корпусов реакторов ВВЭР-1000.

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