ISSN 1818-331X ЯДЕРНА ФІЗИКА ТА ЕНЕРГЕТИКА 2013 Т. 14 № 1

РАДІАЦІЙНА ФІЗИКА

УДК 621.039.53

V. M. Revka, L. I. Chyrko, Yu. V. Chaikovskiy, O. V. Trygubenko

Institute for Nuclear Research, National Academy of Sciences of Ukraine, Kyiv

DIFFERENT APPROACHES TO ESTIMATION OF REACTOR PRESSURE VESSEL MATERIAL EMBRITTLEMENT

The surveillance test data for the nuclear power plant which is under operation in Ukraine have been used to estimate WWER-1000 reactor pressure vessel (RPV) material embrittlement. The beltline materials (base and weld metal) were characterized using Charpy impact and fracture toughness test methods. The fracture toughness test data were analyzed according to the standard ASTM 1921-05. The pre-cracked Charpy specimens were tested to estimate a shift of reference temperature T_0 due to neutron irradiation. The maximum shift of reference temperature T_0 is 84 °C. A radiation embrittlement rate A_F for the RPV material was estimated using fracture toughness test data. In addition the A_F factor based on the Charpy curve shift (ΔT_F) has been evaluated. A comparison of the A_F values estimated according to different approaches has shown there is a good agreement between the radiation shift of Charpy impact and fracture toughness curves for weld metal with high nickel content (1,88 % wt). Therefore Charpy impact test data can be successfully applied to estimate the fracture toughness curve shift and therefore embrittlement rate. Furthermore it was revealed that radiation embrittlement rate for weld metal is higher than predicted by a design relationship. The enhanced embrittlement is most probably related to simultaneously high nickel and high manganese content in weld metal.

Keywords: WWER-1000 reactor pressure vessel, surveillance specimens, neutron fluence, radiation embrittlement, fracture toughness.

Introduction

In the frame of surveillance program for WWER-1000 type reactor in Ukraine the Charpy V-notch impact testing is used as simple and inexpensive method to estimate the fracture toughness curve shift due to irradiation and therefore embrittlement rate for the RPV steels. However, the evidence is needed that Charpy impact test data is valid to estimate the changes in material fracture toughness due to irradiation considering that RPV is subjected to the static loading during the operation. So according to requirements of surveillance program the pre-cracked Charpy V-notch (PCVN) specimens for a direct determination of static fracture toughness are also used to evaluate an embrittlement rate of RPV materials.

It is known from the test reactor irradiation experiment that Charpy impact test data describes well the changes of material fracture toughness because of radiation damages [1]. This observation is valid only if the ductile to brittle transition temperature does not exceed 100 °C. However there is experimental evidence [2] that Charpy impact test data can underestimate a shift of the fracture toughness curve due to irradiation. In this study a comparison of the radiation shift of the Charpy impact and fracture toughness curves has been made from a view point of material embrittlement estimation.

Materials and test methods

The studied materials are 15Ch2NMFAA steels (Cr-Ni-Mo-V steel) and its welds (Sv-12ChGNMAA, welding compound ФЦ-16) which are used for WWER-1000 RPV fabrication. The chemical composition of RPV belt line materials is shown in the Table. Materials are low carbon and low alloyed ferritic steels with ferrite and bainite metallographic structure. The typical heat treatment is quenching with high tempering. The materials are extremely pure with regard to impurities of copper and phosphorus. At the same time welds have a high nickel (1,88 % wt.) and manganese (0,97 % wt.) content that increases their susceptibility to neutron irradiation in spite of the low Cu and P content [3, 4]. For base and weld metal in unirradiated condition the yield strength is about 560 MPa and 480 MPa respectively.

Chemical composition for base and weld metal (% wt)

Element	C	Si	Mn	Cr	Ni	Mo	Cu	S	P	V
Base metal	0,15	0,33	0,48	2,07	1,12	0,53	0,06	0,009	0,007	0,1
Weld	0,06	0,26	0,97	1,80	1,88	0,65	0,02	0,007	0,006	-

Specimens were irradiated in the standard surveillance capsules within the neutron ($E > 0{,}5$ MeV) fluence range of $(12{,}9 \div 46{,}5)\cdot 10^{22}$ m^{-2}. Irradiation temperature was about 300 °C. Surveillance specimens were being irradiated during 16 fuel cycles (~ 4128 days) by neutron flux of about 10^{15} m^{-2}/s that is usual for WWER-1000 type reactor irradiation condition. For the analysis fracture toughness and Charpy impact test data have been used. The RPV material have been tested at scientific center “Kurchatov Institute” (Russia) in the frame of a standard surveillance program for one NPP unit which is under operation in Ukraine.

The standard Charpy specimens (10 × 10 × 55 mm) were used for the estimation of impact energy in the specified temperature range. For this purpose an impact pendulum machine with 300 Joules capacity and the environmental chamber were applied to get the Charpy curves for unirradiated and irradiated materials. A shift of Charpy curves due to irradiation (ΔT_F) is defined according to PNAE G-7-002-86 approach (an index temperature for the Charpy curve depends on the material yield strength).

A three point bend method was applied to test pre-cracked Charpy specimens and determine the fracture toughness parameters (in this case K_{Jc} value, i.e. elastic-plastic equivalent of a critical stress intensity factor). Specimens without side grooves were L-T and L-S oriented for base and weld metal respectively. For test at low temperatures, liquid nitrogen is used to cool the specimens. A fracture toughness analysis has been performed according to the ASTM 1921-05 standard as well as an estimation of the radiation shift of Master curve (ΔT_0).

A radiation embrittlement rate for base and weld metal was estimated using the fluence dependencies of Charpy impact (ΔT_F) and fracture toughness (ΔT_0) curve shift. The PNAE 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 $n = 1/3$) was applied to define a chemistry factor A_F using a statistical analysis.

Experimental results and discussion

The neutron fluence dependencies of transition T_K and reference temperature T_0 shift based on Charpy impact and fracture toughness test data are shown in Figs. 1 and 2 for base and weld metal respectively. For base metal the ΔT_F value obtained from Charpy impact test is consistent with a T_0 reference temperature shift at low neutron fluence. However some discrepancy between two approaches is observed at high neutron fluence. This is most probably related to the relatively high uncertainty in T_0 determination. For this set three of six PCVN specimens have been tested near lower-shelf toughness range that increases the uncertainty in T_0 determination.

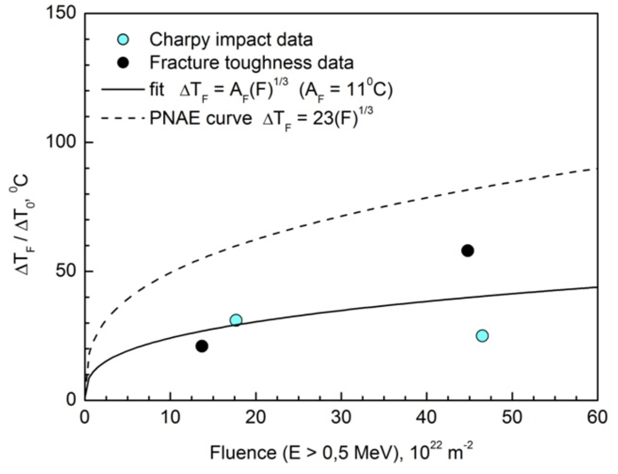

Fig. 1. Neutron fluence dependence of T_K and T_0 shift for base metal. (Charpy impact and fracture toughness test data).

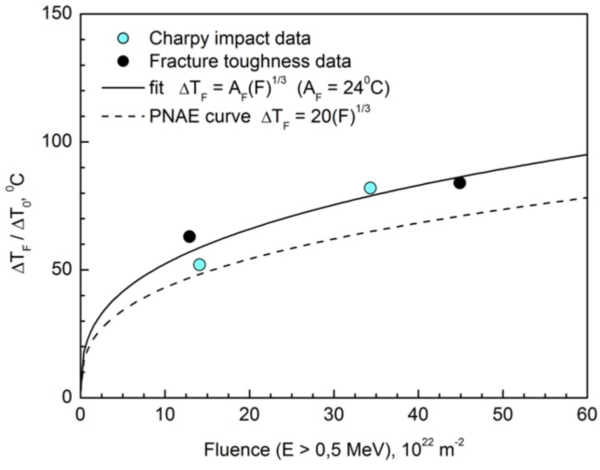

Fig. 2. Neutron fluence dependence of T_K and T_0 shift for weld metal. (Charpy impact and fracture toughness test data).

For weld metal the Charpy impact curve shift is consistent with a T_0 reference temperature shift within studied neutron fluence range. The maximum radiation shift of Charpy impact and fracture toughness curves is 82 and 84 °C respectively for irradiated materials. The results indicate that Charpy impact test data is adequate to describe the changes in material fracture toughness due to the radiation damages and, therefore, to estimate reliably the embrittlement rate for this material irradiated up to neutron fluence $\sim 45\cdot 10^{22}$ m^{-2}.

For comparison a PNAE G-7-002-86 design curves for studied materials (a chemistry factor $A_F = 23$ °C for base metal and $A_F = 20$°C for weld metal) are shown next to the test data points. The chemistry factor A_F estimated from a regression analysis is equal to 11 °C for base metal and do not exceed the PNAE design value (see Fig. 1). For weld metal the statistical analysis gives A_F = 24 °C (see Fig. 2). This results means that weld metal is more susceptible to radiation damages in comparison to base metal.

Furthermore the radiation embrittlement rate for weld metal is higher then predicted by PNAE G-7-002-86 approach. One of the reason for enhanced embrittlement can be the simultaneously high nickel (1,88 % wt.) and manganese (0,97 % wt.) content in weld metal since it is known these alloying element play a crucial role in the radiation embrittlement phenomena in the case of RPV materials [3, 4]. It should be noted the design A_F value does not takes into account a chemical composition of RPV steels that is one of the shortcomings for PNAE G-7-002-86 approach.

Conclusions

In this study the WWER-1000 RPV material embrittlement rate has been evaluated using the surveillance test data for the nuclear power plant which is under operation in Ukraine. A comparison of the radiation shift of the Charpy impact and fracture toughness curves has been made from a view point of material embrittlement estimation. The following conclusions can be drawn:

for weld metal with high nickel content the Charpy impact curve shift is consistent with a T_0 reference temperature shift up to 84 °C;

Charpy impact test data is adequate to describe the changes in material fracture toughness due to the radiation damages and, therefore, to estimate reliably the embrittlement rate for weld metal with high nickel content (1,88 % wt) irradiated up to neutron fluence ~ $45\cdot10^{22}$ m^{-2};

radiation embrittlement rate for weld metal is higher then PNAE G-7-002-86 design approach prediction. One of the reasons for enhanced embrittlement can be the simultaneously high nickel and manganese content in weld metal.

REFERENCES

1. *Alekseenko N.N, Amaev A.D., Gorynin I.V., Nikolaev V.A.* Radiation Damage of Vessel Steels of Water-Water Type Reactors. - Moscow: Energoizdat, 1981. - 192 p.
2. *Wallin K., Valo M., Rintamaa R. et al.* Descriptive characteristics of different types of test for irradiation embrittlement // Nucl. Eng. & Design. - 1995. - Vol. 159. - P. 69 - 80.
3. *Miller M.K., Sokolov M.A., Nanstad R.K., Russell K.F.* APT characterization of high nickel RPV steels // J. Nucl. Mater. - 2006. - Vol. 351. - P. 187 - 196.
4. *Lambrecht M., Almazouzi A.* Positron annihilation study of neutron irradiated model alloys and a reactor pressure vessel steel // J. Nucl. Mater. - 2009. - Vol. 385. - P. 334 - 338.

В. М. Ревка, Л. І. Чирко, Ю. В. Чайковський, О. В. Тригубенко

РІЗНІ ПІДХОДИ ДО ОЦІНКИ ОКРИХЧУВАННЯ МАТЕРІАЛІВ КОРПУСІВ РЕАКТОРІВ

Дані зразків-свідків для корпусу реактора ВВЕР-1000 промислової АЕС, що експлуатується в Україні, були використані для оцінки ступеня окрихчування матеріалів. Було проведено аналіз результатів випробувань на ударний вигин та в’язкість руйнування для матеріалів корпусу реактора напроти активної зони (основний метал та метал зварного шва). Результати випробувань на в’язкість руйнування були оброблені згідно з вимогами стандарту ASTM 1921-05. Зразки Шарпі з тріщиною були випробувані, для того щоб оцінити зсув референсної температури T_0 внаслідок опромінення. Максимальний зсув T_0 84 °С. Використовуючи дані по в’язкості руйнування, були визначені коефіцієнти радіаційного окрихчування A_F для досліджених матеріалів. Крім того, коефіцієнти A_F були оцінені на підставі даних по зсуву кривої Шарпі (ΔT_F). Порівняння значень A_F, отриманих згідно з різними підходами, показало, що існує узгодженість між радіаційними зсувами кривої Шарпі та в’язкості руйнування для металу зварного шва з підвищеним вмістом нікелю (1,88 % мас.). Отже, дані по випробуванням на ударний вигин можуть бути використані для оцінки зсуву кривої в’язкості руйнування та ступеня окрихчування. Крім того, було виявлено, що ступінь радіаційного окрихчування зварного шва вище в порівнянні з проектною величиною. Підвищене окрихчування, скоріше за все, обумовлено одночасно високою концентрацією нікелю та марганцю в металі шва.

Ключові слова: корпус реактора ВВЕР-1000, зразки-свідки, флюенс нейтронів, радіаційне окрихчування, в’язкість руйнування.

В. Н. Ревка, Л. И. Чирко, Ю. В. Чайковский, А. В. Тригубенко

РАЗЛИЧНЫЕ ПОДХОДЫ К ОЦЕНКЕ ОХРУПЧИВАНИЯ МАТЕРИАЛОВ КОРПУСОВ РЕАКТОРОВ

Данные образцов-свидетелей для корпуса реактора ВВЭР-1000 промышленной АЭС, находящейся в эксплуатации в Украине, были использованы для оценки степени охрупчивания материалов. Был проведен анализ результатов испытаний на ударный изгиб и вязкость разрушения для материалов корпуса реактора напротив активной зоны (основной металл и металл сварного шва). Результаты испытаний на вязкость разрушения были обработаны согласно требованиям стандарта ASTM 1921-05. Образцы Шарпи с трещиной были испытаны, чтобы оценить сдвиг референсной температуры T_0 вследствие облучения. Максимальный сдвиг T_0 составляет 84 °C. Используя данные по вязкости разрушения, были определены коэффициенты радиационного охрупчивания A_F для исследуемых материалов. Кроме того, коэффициенты A_F были оценены на основании данных по сдвигу кривой Шарпи (ΔT_F). Сравнение значений A_F, полученных согласно различным подходам, показало, что существует согласованность между радиационными сдвигами кривой Шарпи и вязкости разрушения для металла сварного шва с повышенным содержанием никеля (1,88 % мас.). Следовательно, данные по испытаниям на ударный изгиб могут быть использованы для оценки сдвига кривой вязкости разрушения и степени охрупчивания. Кроме того, было обнаружено, что степень радиационного охрупчивания сварного шва выше по сравнению с проектной величиной. Повышенное охрупчивание, скорее всего, обусловлено одновременно высокой концентрацией никеля и марганца в металле шва.

Ключевые слова: корпус реактора ВВЭР-1000, образцы-свидетели, флюенс нейтронов, радиационное охрупчивание, вязкость разрушения

Надійшла 11.10.2012
Received 11.10.2012