PROLONGATION OF NUCLEAR POWER PLANT LIFETIME

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Abstract: Topic of this paper is material research of 15Kh2MFAA reactor pressure vessel (RPV) steel regarding the possibility of prolongation of NPP lifetime. During service, reactor pressure vessel steels are exposed to several factors, which causes microstructural changes and degradation of the mechanical properties such as neutron irradiation and thermal stress. For these reasons high quality and reliability of reactor pressure vessel steels is required and there is need to know degradation processes, which affect condition and further behaviour of steels. This paper is focused on evaluation of microstructural quality of Russian steel 15Kh2MFAA and effects of thermal annealing on non-irradiated specimens and its microstructural changes using non-destructive method called positron annihilation spectroscopy.

Keywords: annealing, structural materials, positron annihilation spectroscopy, 15Kh2MFAA

1 INTRODUCTION

During service, reactor pressure vessel (RPV) steels are exposed to neutron irradiation, high pressure and temperature, which causes microstructural changes and a degradation of the mechanical properties. As the ages of existing NPPs are increasing and lifetime extensions and EOL (end of life) up to 80 years for existing and new NPPs are on the agenda, some existing open issues regarding the understanding and prediction of RPV irradiation embrittlement effects need to be clarified. The reactor pressure vessel (RPV) is a key safety component, because it not only operates at elevated pressures and temperature, but also contains the reactor and its fission products. Additionally, in `life management' terms it is usually considered as an `irreplaceable component'. It has to accommodate all the functional requirements arising from normal nuclear power plant(NPP) operating conditions as well as those loads, resulting from improbable events, without failing because a duplicate or redundant back-up system does not exist. A disruptive RPV failure could destroy all barriers– cladding, fuel and containment, and lead to large releases of radioactivity. It is therefore essential to demonstrate a high reliability for the pressure vessel coupled with a low probability of failure. It is also necessary to demonstrate that there are adequate margins for anticipated loading conditions to the end of its operational life. The RPV has to be manufactured and tested to high standards to demonstrate its reliability (which includes non-destructive examination) before and during operation. So, if the RPV is built from appropriate materials, using reliable design codes, built (manufactured) to well-tried methods, high standards, tested and operated (in the way assumed in the design) correctly, the RPV integrity will depend, basically, on the materials' mechanical properties and the extent which they degrade during operation.It is therefore important to periodically evaluate current state of the RPV and provide advanced information about condition of this NPP´s life limiting component. In this paper we analyse and evaluate the effects of thermal annealing on structural materials of RPV, especially Russian steel 15Kh2MFAA, which has been used in WWER 440 reactors. We measured and analysed the microstructural damage of each specimen of steel which were exposed to various temperatures.

2 SPECIMENS

As a basic structural material in WWER 440 RPV is used a ferritic steel 15Kh2MFAA containing 0.25-0.35 wt% V and low amount of Ni (max. 0.40 wt%) (table 2.1). Vanadium had been added to the earlier steels to increase resistance to thermal ageing, produce a fine grained tempered bainite which imparted strength [1]. Microstructure of 15Kh2MFAA reactor steel is shown in figure 2.1.

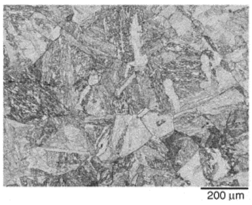
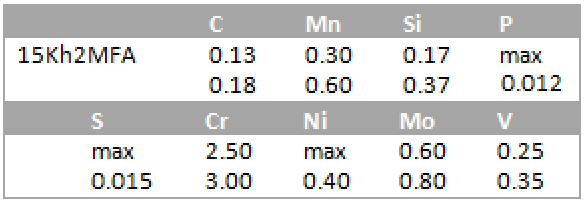


Fig.2.1: *Microstructure of 15Kh2MFAA steel [2].*

Tab.2.1: *List of chemical components(wt%) of 15Kh2MFAA steel[1].*



	C	Mn	Si	P
15Kh2MFA	0.13 0.18	0.30 0.60	0.17 0.37	max 0.012
S	**Cr**	**Ni**	**Mo**	**V**
max 0.015	2.50 3.00	max 0.40	0.60 0.80	0.25 0.35

Each specimen of 15Kh2MFAA reactor steel was cut into the size 10x7x0.2 mm and polished by 1µm diamond paste. At first all specimens were measured in as-received state and afterwards they were gradually annealed to 300, 400 and 450°C in laboratory muffle-furnace. During the annealing process the specimens were stored inside the test tube with argon atmosphere at atmospheric pressure. Specimens were annealed for 2 hours at a given temperature and cooling rate after the annealing process was approximately 1°C/min.

3 EXPERIMENTAL TECHNIQUE – PALS

Positron annihilation lifetime spectroscopy is well-established non-destructive spectroscopic method for evaluation of defect-size(size of clusters) in material and its density by positron annihilation intensity. Sensitivity of PALS is relatively very high with ability to recognize one defect per 10^7 atoms [3]. These defects cannot be seen by electron microscope, so PALS can, and in this sense itprovides a unique type of information for microstructural studies of selected materials before and after external treatment (irradiation, annealing, etc.).

PALS is based on positron (e+) annihilation with electron (e−)where the positron is produced by + decay (-photon with energy1270 keV is emitted providing start signal for PALS technique)and afterwards thermalizes (~1 ps) and diffuses in the specimen(~100 nm). Subsequently the positron is trapped in vacancy-typedefect due to an attractive potential in volume defects that exists there because of the lack of positively charged nuclei (repulsive forces). After some time, depending on the defect size and electrondensity, the positron recombines with an electron and annihilates with emission of two -photons (511 keV – stop signal for PALS) [4].

Our PALS equipment has a time resolution about 2 ps. Non-radioactive specimens (as-received and implanted) were measured with two detectors set-up and irradiated specimens were measured with three detectors set-up due to induced radioactivity (mainly from 60Co caused by transmutation process). Source of positrons was 22Na in Kapton foils. Interpretation of measurements is done using LifeTime 9 program where we evaluate 1 as an annihilation in bulk, 2 as an annihilation in defects and 3 is an annihilation outside from a sample (air).

4 PALS RESULTS

In the beginning of analysis of the effects of thermal stress on microstructural quality of reactor steel 15Kh2MFAA were specimens measured in as-received state. Each specimen (of 5 equal available) was annealed at specific temperature (300, 400 and 450°C) and subsequently measured. Quality of microstructure or level of damage of crystal lattice due to increased temperature was evaluated by positron lifetime in bulk (τ_1), intensity of annihilation in bulk (I_1), positron annihilation in defects (τ_2) and its intensity (I_2) and average positron lifetime in material (τ_{avg}). Average positron lifetime in material is a qualitative factor of the microstructure expressing average lifetime of a positron in bulk and in defects. It is a similar parameter as mean lifetime (MLT) but τ_{avg} does not consider positron annihilation in the air (τ_3) which can distort the microstructural quality evaluation.

$$MLT = I_1.\tau_1 + I_2.\tau_2 + I_3.\tau_3 \qquad (4.1)$$

$$\tau_{avg} = I_1.\tau_1 + I_2.\tau_2 \qquad (4.2)$$

For as-received state of reactor steel 15Kh2MFAA is positron lifetime in bulk 85-95 ps. Positron lifetime in defects is 208-221 ps what indicates presence of di- or 3-vacancy types of defects. Level of the intensity of annihilation in defects is 50-60% which means higher presence of relatively smaller defects. These defects occur in crystal lattice since manufacture or could arise during storage or preparation of specimens. Layout of these defects is balanced and does not form bigger clusters of vacancies and therefore does not present a problem in microstructural quality of the material.

Positron lifetimes in bulk along with intensities for all measured specimens are shown in figure 4.1. Figure shows that positron lifetime in bulk increases with higher temperature to 100 ps what corresponds with theoretical rate of positron lifetime in bulk for pure Fe [5].

Tab. 4.1: Positron lifetime for different types of defects in pure Fe [5].

Material	Positron lifetime (ps)
bulk	110
dislocations	165
mono-vacancies	175
di-vacancies	197
3-vacancies	232
4-vacancies	262
6-vacancies	304

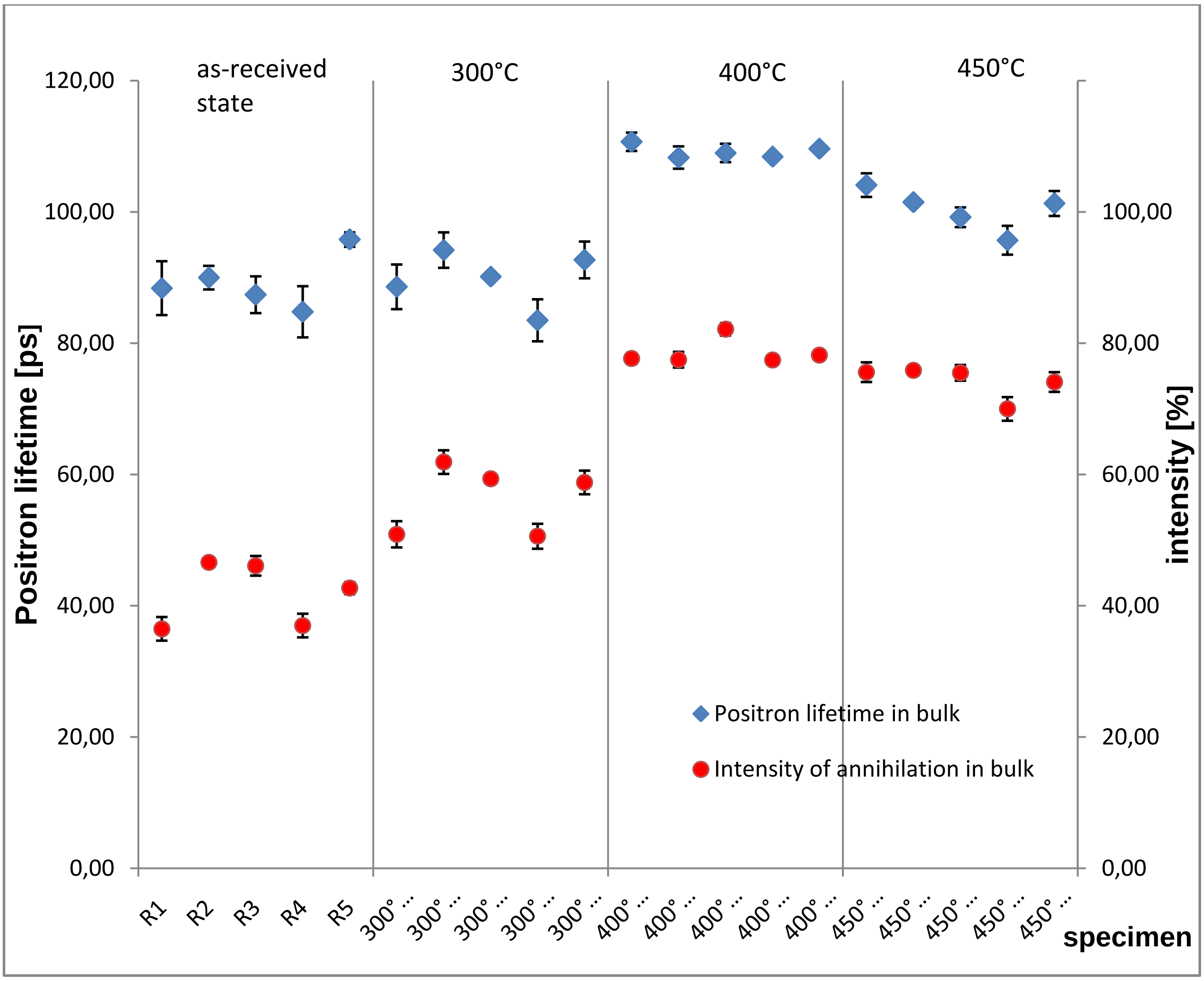


Fig. 4.1: Positron annihilation in bulk.

Intensity of positron annihilation in bulk has increasing trend with increasing temperature. The level of intensity I_1 by 400 and 450°C is 75-80% what means 35% increment against as-received state. This intensity increment shows that the higher the temperature is, the higher crystal lattice recovery occurs. This happens due to the fact that higher temperature increases energy of defects (for example interstitials) and they diffuse easier within the material.

Positron lifetimes in defects along with intensities for all measured specimens are shown in figure 4.2. Figure shows that positron lifetimes in as-received state and in 300°C specimens is equal at level 210-225 ps what indicates di- or 3-vacancy type of defects. Defects intensity by 300°C specimens has decreased against as-received state by approximately 15% what could means that by the same size of defects there is smaller density of defects in crystal lattice. This conclusion corresponds with figure 4.1 where increment of annihilation intensity in bulk with increased temperature is shown.

With temperature increment to 400°C positron lifetimes in defects reached level 280-300 ps what represents defects of 5- to 6-vacancies. At the same time significant decrement of annihilation intensity in defects occurs (15-20%). This effect is probably caused by higher migration of individual defects in material due to increased temperature. These defects could form bigger cluster causing prolongation of positron lifetime in defects $\tau_2$and decrement of annihilation intensity I_2.

With temperature rising up to 450°C, which is almost actual annealing temperature of RPVs, intensity of annihilation in defects remained practically the same. Difference between 400°C specimens is at the level of positron lifetimes in defects which decreased under 260 ps and therefore we could assume that the annealing of defects and certain recovery of crystal lattice of 15Kh2MFAA steel occurred.

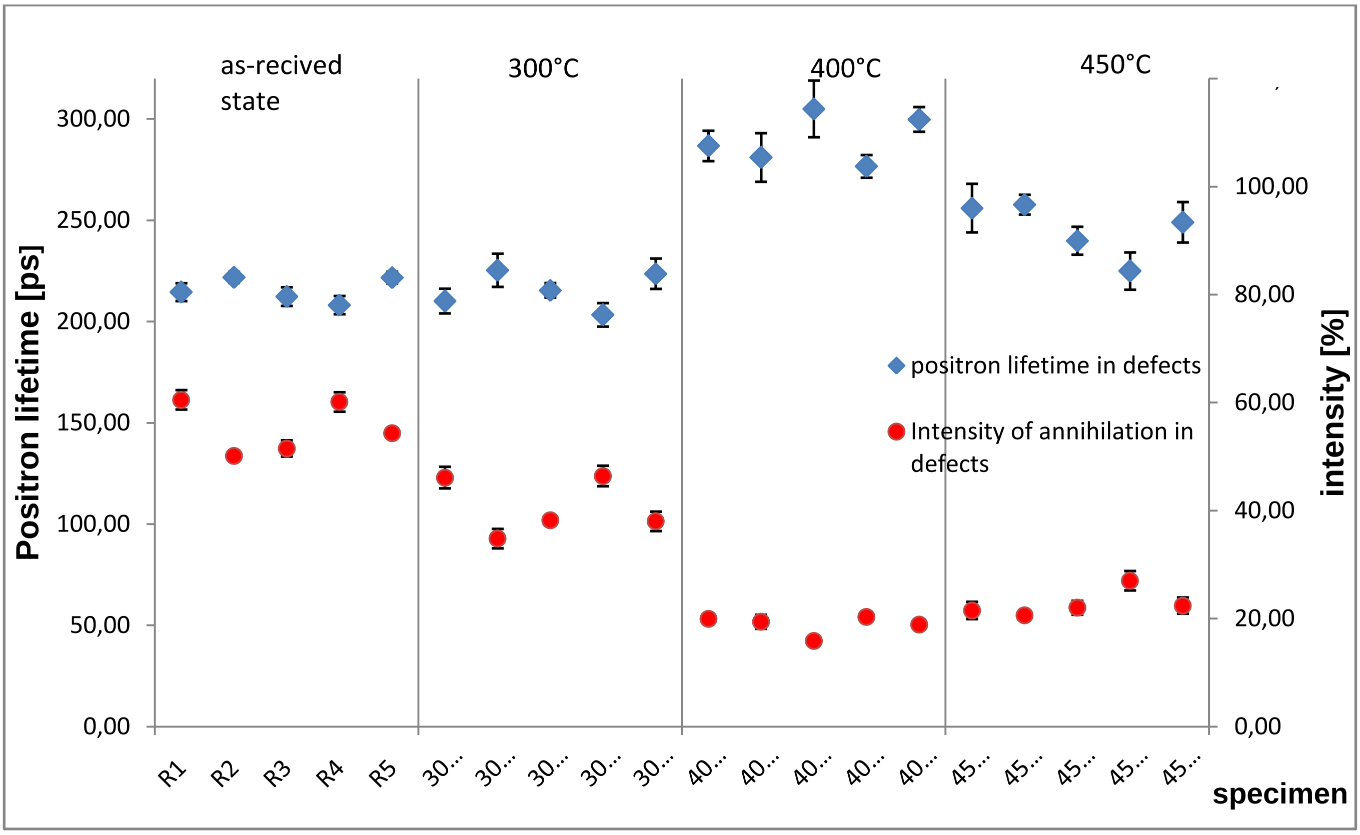


Fig.4.2: Positron annihilation in defects.

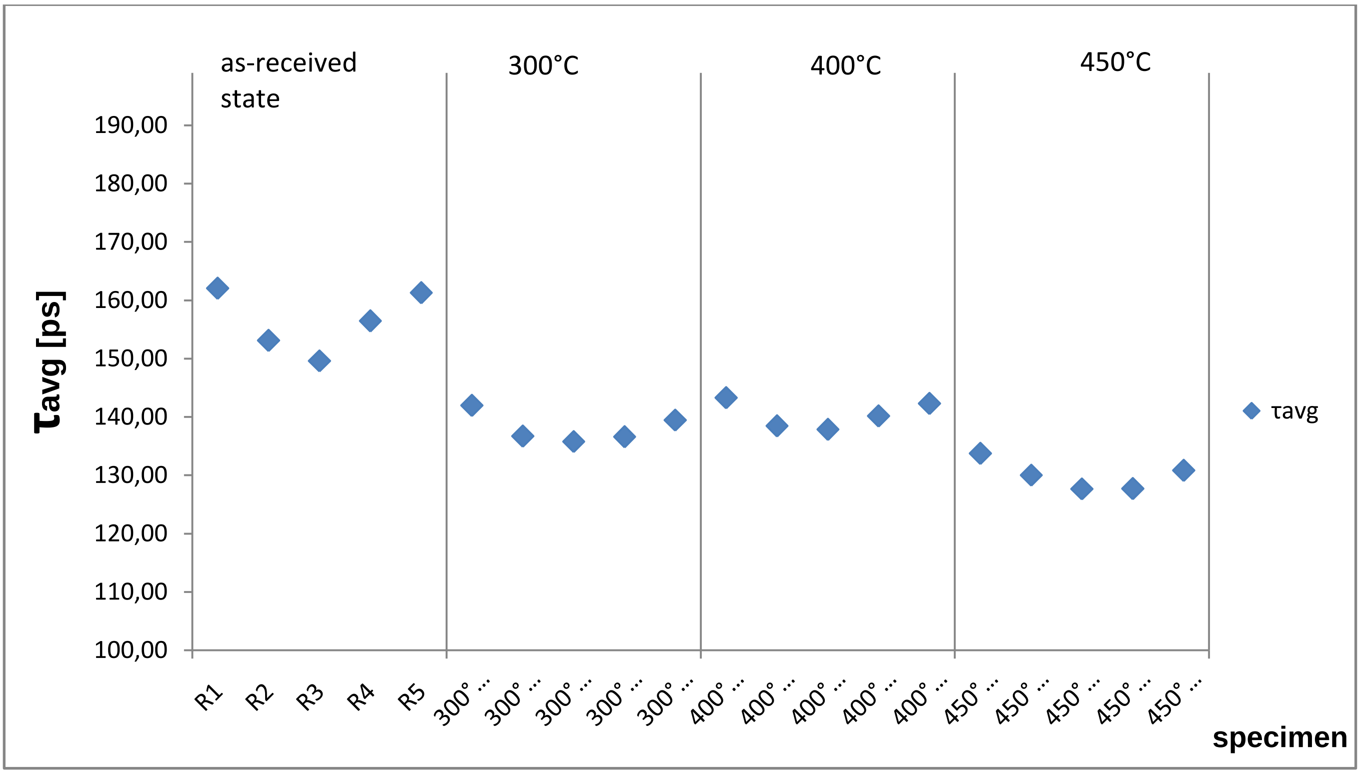


Fig.4.3: Graph of τ_{avg} values.

Values of average positron lifetime in material (τ_{avg}) for as-received state range from 150-160ps what indicates presence of dislocations or monovacancies in crystal lattice.As expected the lowest values of $\tau_{avg}$was by specimens annealed at 450°C when according to the theory recovery of microstructure should occur.

Values of τ_{avg} decreased to level of about 130 ps (fig. 4.3).

6 CONCLUSION

The PALS is one of the non-destructive spectroscopic methods which can contribute to the complex evaluation of the RPV-steels microstructure and can in this way contribute to the nuclear safetyof NPPs or their feasibility to the long-term operation. This paper was focused oneffects of thermal stress on structural materials of RPV, especially former Soviet Union steel 15Kh2MFAA which has been used in WWER 440 reactors operating in Slovakia. Each specimen was gradually exposed to various temperatures (300, 400 and 450°C) and measured. Data obtained from PALS has shown that lower temperatures do not significantly affect the size of defects in crystal lattice. However, by reaching specific temperature a significant growth of defects and annihilation in bulk occurs. Positron lifetime in defects slowly decreases with temperature growing to final 450°C, i.e., larger clusters of vacancies fall apart and form smaller ones, what could be considered as crystal lattice recovery.The rate of material recovery after thermal annealing (450°C) haven´t reached expected values compared to the specimens in as-received state. This could happen due to short period of thermal annealing (only 2 hours) when defects didn´t have enough time to diffuse and crystal lattice recovery haven´t occurred. Second reason for these observations could be insufficient annealing temperature (450°C) compared to the real temperature during which RPVs are annealed (475-500°C).

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