Investigation of VVER-1200 reactor pressure vessel’s material

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Abstract. At high temperature and pressure, the reactor materials are exposed to various radiation. Irradiation causes significant changes in the crystal structure and their mechanical properties. The mechanical properties of low alloy steels generally do not change so much with temperature. The aim of this research is to prepare the basic measurements to investigate 15Cr2NiMoVA steel, according to MSZ EN ISO 148-1:2017. Charpy impact test was made at different temperatures from -75 °C to 200 °C. Potentiodynamic tests were used to determine the corrosion rate. During the optical microscopy measurement, MnS inclusions were found in the examined material.

1. Introduction

The pressure reactor vessel (RPV) is one of the important equipment that ensures stable operation of the reactor by limiting variations of the reactor coolant system (RCS) pressure within allowed tolerances [1], so it limits the pressure change within permissible value during operational transient and prevents the primary coolant system from overpressure in accidental scenarios [2,3]. It follows that it is operated at high temperature and pressure, neutron radiation, thermal ageing and low cycle fatigue, which are the main environmental effects that degrade the RPV material properties during service [1,4]. According to this loading, the vessel material is degraded during the operation. In the Russian VVER type reactor [5] higher amount of Cr steel is used for pressure vessel [6]. These are the VVER-1200 water-moderated and water-cooled power reactors [7]. The protection against the irradiation, corrosion and fracture had to be guaranteed. The irradiation embrittlement, caused by long-term irradiation with high-energy neutrons, is coming with together mechanical property changes such as an increasing hardness, yield stress, and tensile strength, and a decrease of toughness [8,9]. The mechanical properties of low alloy steels generally do not change so much with temperature. The material is covered with a stainless steel layer made by cladding to protect it from the general corrosion. This layer has to be a homogenous thickness and a good sacrificial barrier against high-temperature oxidation in several microns [10]. Besides, the major parameter is the ductile to brittle transition temperature. It has to occur at the lowest temperature reachable taking into account the steel composition and mechanical properties [11].

The investigation of the reactor vessels is beloved by all. Firstly, Chernobaeva et al. [12] investigate a previous type of reactor. They used 15Cr2NiMoVA steel which received from a VVER-1000 reactor as irradiated and aged. Standard 10×10 and ‘mini’ 5×5 Charpy specimens were used in this research to compare the results of the different size of samples. A correlation was found between both size of samples. It makes possible to incorporate test data for mini-Charpy specimens into a database of
VVER-1000 RPV materials based on this equitation: $T_{k}^{10 \times 10} = 0.99 \times T_{k}^{5 \times 5} + 51 \pm 2 \sigma$ ($\sigma = 12.7$, $T$ is the temperature of the signed samples).

Anosov et al. [13] investigated the differences between the critical brittleness ($T_{C}$ – which is the temperature of the intersection of the temperature-impact strength curve with the level of determining the transition temperature by the steel yield strength) and the brittle-viscous transition ($T_{T}$ – which was characterized by the steep rise position in the curve of the temperature dependence of the absorbed energy) temperature of 15Cr2NiMoVA steel. $T_{C}$ are significantly lower than the $T_{T}$. The differences is 22 °C. It can be stated, the transition temperature is better to define the brittle fracture of the VVER-vessels.

Shtrombakh et al. [14] investigated the effect of the Ni content on the thermal and radiation resistance. The previous steel was examined with modified Ni content. Lower Ni content led to the lower density of radiation-induced precipitates under irradiation.

These researches were adapted to the nuclear power plant operation of their own country. Every country has a different condition in the reactors because of its consumptions. Therefore, the aim of this paper is to get insight into the selection of the materials and prepare to investigate the material of the reactor.

2. Materials and methods

In this study 15Cr2NiMoVA steel was used with the following chemical composition: 0.14% C, 2.6% Cr, 0.31% Ni, 0.79% Mo, 0.63% V, 0.67% Mn, 0.08%P, 0.28% Si, 0.33% Cu, Fe in balanced. Ferenc Gillemot provided the Charpy results of the samples in normal and aged conditions from MTA Research Institutes. (The pre-heat treatment of the samples was unknown for us.)

Olympus optical microscope was used to investigate the cross-section of the samples. The surface of the cross-section was mechanically ground with 80 to 2500-grit SiC paper and polished with 3 μm diamond suspension. The samples were cleaned with acetone and dried with hot air. The fracture of some of the samples was observed by Olympus SZX16 stereomicroscope. The corrosion resistance of the samples was evaluated by measuring polarisation curves in boron aqueous solution at 150°C using ZAHNES IM6e electrochemical working station. The cell of the specimen was set-up as the working electrode, a $\text{Hg}_2\text{Cl}_2/\text{KCl}$ calomel electrode as the reference electrode and platinum were used as the counter electrode. The composition of the corroded surface was measured by Zeiss EVO MA10 scanning electron microscope (SEM) and analysed by energy-dispersive spectrometry (EDS).

3. Results and discussion

3.1. Charpy impact test

The results of the Charpy impact test at different temperatures and conditions were summarised in Table 1 and their transition temperature diagram is seen in Fig. 1. The transition temperature was calculated to use the hyperbolic tangent according to (1). It fits the relationship between the impact absorption energy equation ($e$) and test temperature ($T$).

$$e(T) = A + B \times \tanh \frac{T - T_{0}}{C}$$ (1)

where $C$ is half of the transition temperature range from minimum to maximum value and $T_{0}$ is for the temperature when $e(T)$ equals to the minimum value; $A$ corresponds to the minimum energy and $B$ to the maximum energy [15]. The transition temperature was between the brittle and ductile state is
-20 °C in normal and -7 °C in aged condition. The impact energy differences at operational temperature are 20 J, but the required value is 41 J, which lower than the results. To compare with [16] in the same condition, the results are similar, only a few J differences can be found at higher temperature.

### Table 1. Results of Charpy impact test in different temperature

| Temp. (°C) | KV (J) | e (mm) | Temp. (°C) | KV (J) | e (mm) |
|------------|--------|--------|------------|--------|--------|
| -75        | 11     | 0.07   | -60        | 4      | 0      |
| -70        | 19     | 0.1    | -60        | 13     | 0.18   |
| -70        | 13     | 0.18   | -60        | 13     | 0.09   |
| -60        | 12     | 0      | -40        | 56     | 1.04   |
| -50        | 12     | 0.2    | -40        | 61     | 0.46   |
| -50        | 38     | 0.5    | -40        | 60     | 0.69   |
| -36        | 19     | 0.16   | -20        | 98     | 0.80   |
| -30        | 48     | 0.7    | -20        | 82     | 0.76   |
| -30        | 33     | 0.36   | -20        | 88     | 0.71   |
| -21        | 133    | 1.75   | -20        | 80     | 0.75   |
| -15        | 93     | 1.46   | 20         | 100    | 1.11   |
| -10        | 92     | 1.29   | 40         | 116    | 1.60   |
| 20         | 86     | 2.15   | 40         | 125    | 1.54   |
| 40         | 116    | 2.08   | 200        | 174    | 1.78   |
| 200        | 163    | 2.15   | 200        | 182    | 1.53   |
| 200        | 165    | 2.08   | 200        | 182    | 1.52   |

Stereomicroscopic images are seen in Fig. 2. from the fractured surface. As it is observed, at low temperature, the material was brittle, while at high temperature it was tough. At the operational temperature, the material has to be tough because of the loadings.

**Figure 2.** Fractured surface after the Charpy impact test. left: at -30 °C, right: at 200 °C

### 3.2. Microstructure

Fig. 3 shows the optical microscopic images of the investigated material. As it is seen in Fig. 3 the microstructure was ferrite and bainite. It can be created during the pre-heat treatment. In higher magnification inclusions were found which is seen in Fig. 3. To analyse the inclusion, SEM-EDS was used to measure the composition.

The main component of the inclusion was sulphur and in large amount iron and manganese were found. The material was contained MnS inclusions which were not resulted by the irradiation because these samples have not been irradiated.
3.3. Corrosion test
In general, the standards for the primary coolant circuit of VVER reactors water chemistry adjusted by additions of $\text{H}_3\text{BO}_3$, KOH, $\text{NH}_4\text{OH}$ [17], so a 10% boron aqueous solution was used for the corrosion test. The solution was contained 10 g Boron and 1000 ml distilled water. Fig 4. shows the polarisation curves after different times. The calculated corrosion rates [18] are listed in Table 2. Based on the calculated corrosion rates, the material has bad corrosion resistance. Neither the corrosion potential nor the current density of the samples considerably changed. As it is seen, the corrosion rates were not changed over the corrosion time. In this condition, this material is not recommended for a reactor, but the corrosion rate can be decreased by cladding, which can be an X8CrNiTi18-10 stainless steel layer on the inner surface. The utilisation of a Cr content film on the inner surface of steel cladding has been considered to hinder fuel-cladding chemical interaction [19].

| time (h) | $E_{\text{corr}}$ (V) | $i_{\text{corr}}$ (µA) | corr. rate (mm/year) |
|---------|-----------------|-----------------|-------------------|
| 1       | -0.57           | 99              | 0.99              |
| 5       | -0.57           | 98              | 0.99              |
| 12      | -0.56           | 98              | 0.99              |
| 24      | -0.55           | 98              | 0.99              |

4. Conclusion
According to our research, the material was though based on the Charpy impact test in both of the normal and aged condition, which was examined close to the operational temperature. Based on the results, the slope of the tangent has decreased by aged specimens, which occurs the value of TTKV changing to a direction unfavourable to us. The TTKV changing should be taken into account by power plants. Next step in our research to examine the effect of neutron flux by reactor vessel how can influence the ductile to brittle transition temperature and though.

Any segregation was not found. In contrast, MnS inclusions were observed. The corrosion resistance of the pure material without the cladding layer was low.
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