IAEA Technical Meeting on “Degradation of Primary System Components of Water Cooled Nuclear Power Plants: Current Issues and Future Challenges”, 5.-8. November 2013, Vienna

Radiation response of the overlay cladding from the decommissioned WWER-440 Greifswald unit 4 reactor pressure vessel

Hans-Werner Viehrig*, Eberhard Altstadt** and Mario Houska***
* Group Leader, ** Head of Department, *** Research Scientist
Helmholtz-Zentrum Dresden-Rossendorf, Institute of Ion-Beam Physics and Materials Research, Bautzner Landstraße 400, 01328 Dresden, Germany

Introduction

Austenitic overlay cladding has been originally designed to protect the low alloyed RPV base and weld metals against corrosion. Usually, the overlay cladding remains out of consideration in the current RPV integrity assessment regulatory codes [1, 2]. Some codes allow the inclusion of the overlay cladding on condition that its properties are known during the RPV lifetime [2, 3]. The fracture behaviour of an operating nuclear reactor pressure vessel, particularly during certain overcooling transients, may strongly depend on the properties of the irradiated overlay cladding [4]. Low fracture toughness and the occurrence of brittle failure at elevated temperatures raise concerns over the potential adverse impact of the austenitic overlay cladding on the integrity of the RPV during a PTS transient. The growth of a surface flaw can lead to the failure of the cladding and significantly increase the probability of vessel failure [4-7].

The most realistic evaluation of the toughness response of RPV overlay cladding to irradiation may be achieved by directly studying RPV wall samples taken from decommissioned RPVs. Such a possibility is available with the investigation of samples taken from the RPV of the Greifswald NPP. Four WWER-440/V-230 nuclear reactors representing the first generation of this reactor type were operated between 11 and 15 years and were decommissioned in 1990. Trepans were extracted from the RPV of the Greifswald units.

This paper presents the test results measured on the austenitic overlay cladding of trepans sampled from different locations within the reactor core region of the Greifswald Unit 4 RPV, which was shut down after 11 operating cycles. The main focus is on the measurement of the crack extension curves and the evaluation of initiation fracture toughness values according to the test standard ASTM E1820-11.

2. Material and specimens

The RPV of the Greifswald unit 4 reactor is overlay cladded by austenitic stainless materials using automatic submerged welding methods. The overlay cladding is welded with several passes using ribbon material of different composition, and hence represents a multilayer structure. The cladding was welded in two-layers overlay with three welding passes [8, 9]:

- first layer (one pass) with a thickness of 3 to 4 mm: ribbon of Sv 07Cr25Ni13 and OF-10 flux, and
- second layer (two passes) with a thickness of 6 to 9 mm: ribbon of Sv 08Cr19Ni10Mn2Nb and OF-10 flux.

Consequently, the total thickness of the cladding amounts 8-10 mm after mechanical machining.

The welding of the cladding and the assembling of the forged rings that form the RPV were performed simultaneously, with the aim to reduce the number of heat treatments. Within these technological processes the cladding in the core region of the RPV, which includes the forged base metal ring 0.3.1. and the welding seam SN0.1.4., was tempered five times in the temperature range 660-675°C with a total duration of 50 h [16]. The overlay cladding contains up to 8% δ-ferrite to avoid hot cracks.

The overlay cladding materials investigated were extracted from the decommissioned WWER-440/V-230 Unit 4 RPV of the Greifswald NPP. The trepans were taken from the circumferential beltline welding seam SN0.1.4 (trepans 4-4 and 4-6) and from the forged base metal ring 0.3.1 in the region of the maximum neutron flux (trepan 4-1). The trepans were cut into discs over the RPV wall thickness using a wire travelling electric discharge machine. The cutting scheme is exemplarily depicted for the trepan 4-1 in Figure 1. As first work step a vertical cut was made to transfer the former orientation of the trepan in the RPV to the discs to be cut. In the following step the curvature at the inner side of the trepan was cut to get a plane reference surface followed by the cutting of the discs as shown in Fig. 1. The first disc towards the inner RPV wall contains the overlay cladding. From this disc 14 Charpy size SE(B) specimens in L-S (specimen axis along vessel circumferential direction and crack growth direction in the vessel radial direction) orientation according to ASTM E1823 were machined. In addition sub-sized rectangular flat tensile specimens were machined from broken halves of the tested Charpy size SE(B) specimens as schematically depicted for the trepan 4-1 in Fig. 2. From one halve 2 specimens from the first layer and 4 specimens from the second layer of the overlay cladding were machined. The orientation of the tensile specimens is L (specimen axis along vessel circumferential direction) according to ASTM E1823.

Table 1 summarises the distances of the crack tips from the RPV inner wall and the belonging neutron fluences. Fig. 3 gives an overview about the crack tip location in the structure of the investigated overlay cladding. In the trepans 4 4 and 4 6 from the welding seam SN0.1.4. the crack tips are located in the 2nd layer welded with the Sv 08Cr19Ni10Mn2Nb ribbon, and the cracks moves towards the RPV inner wall surface during the fracture mechanics testing. The cracks in the specimens from trepan 4-1 were machined from the inner RPV wall surface towards the base metal, hence the crack tip is located in the 1st layer of the cladding welded with the Sv 07Cr25Ni13 ribbon. Generally, it has to be taken into account that the locations of the crack tips vary within one disc because of the curvature of the RPV and differences of the fatigue crack length. The difference can amount up to 0.25 mm.

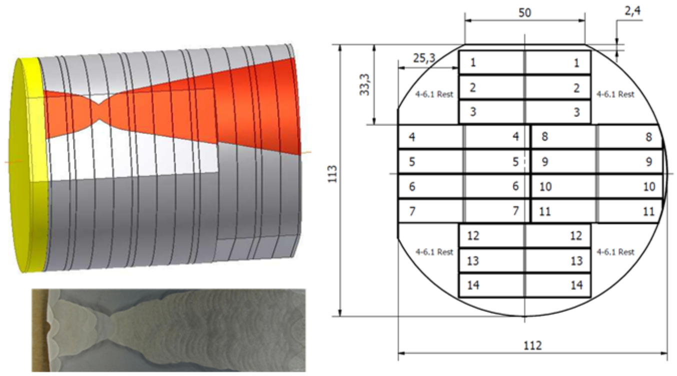

Fig. 1 Picture and cutting scheme of trepan 4-1.

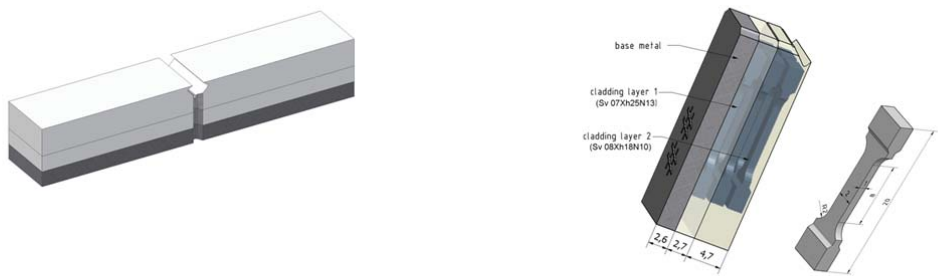

Fig. 2 Charpy size SE(B) specimen and scheme of the machining of sub-size tensile specimens from broken halves.

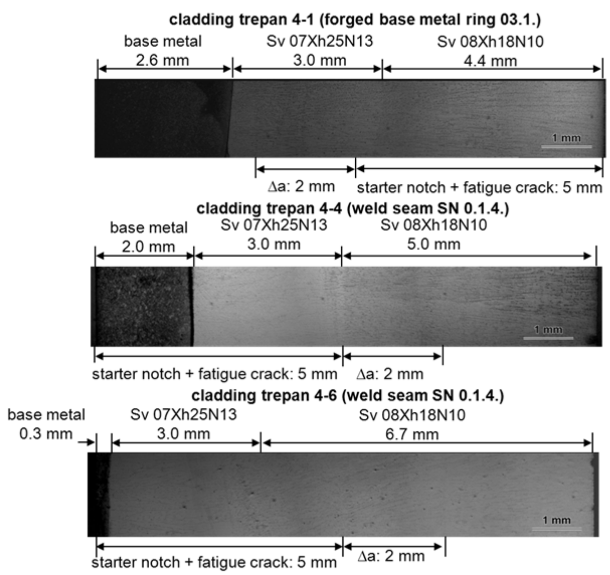

Fig. 4 Overview about the structure of the investigated overlay cladding from the individual trepans and the location of the crack tip.

Table 1 Positions and accumulated neutron fluences of the investigated cladding materials [10,11,12].

code of the trepan and disc	location of the trepan in the Unit 4 RPV	distance of the crack tip location from inner surface mm	Φ (E>0.5MeV) 10^{18} n/cm2
4-1.1	base metal ring No. 0.3.1	9.3	53.73
4-4.1	beltline welding seam No. SN0.4.1.	7.8	41.04
4-6.1		7.5	41.06

3. Testing and evaluation

The irradiated specimens were tested remote controlled with a servohydraulic testing system installed in a hot cell laboratory. Tensile testing was conducted with the sub-sized rectangular flat specimens as displayed in Fig. 2 in a temperature range of -75 to 270°C. The specimens were loaded with an actuator speed of 0.25 mm/min.

Crack extension curves were measured with Charpy size SE(B) specimens using the unloading compliance technique according to ASTM E1820-11 [15].

4. Results and discussion

Fig. 4 shows the yield and ultimate tensile strength vs. test temperature of the investigated overlay cladding materials. As depicted in Fig. 4 there is a minor difference between both layers, in terms of the development of the yield and ultimate tensile strength. These values are about 30% higher than the yield strength of 314 MPa and ultimate tensile strength of 490 MPa for the initial condition of the WWER-440 overlay cladding as reported in [8].

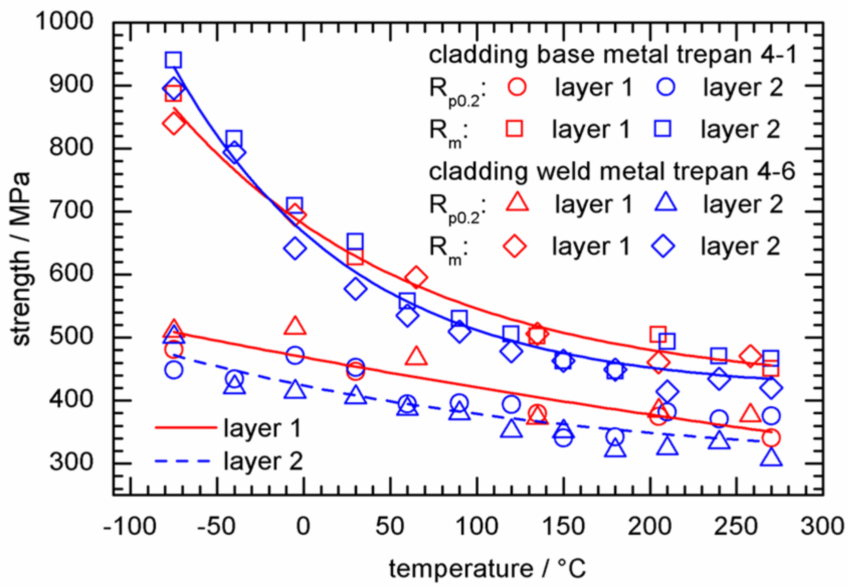

Fig. 3 Tensile strength characteristics of the cladding layers 1 and 2 vs. temperature.

Figs. 5 and 6 depict the K_{JQ} values vs. temperature. Generally, the scatter of the K_{JQ} values is large. The reasons for the scatter are seen in slight uncertainties of the J-Δa measurement by using the UC method and in the heterogeneous structure of the overlay cladding. Especially the J-Δa data determined from the first partial unloading sequences tend to scatter, which has a strong impact on the evaluated crack initiation J_Q values. The trend of the K_{JQ} vs. temperature values is approximated by a polynomial fit. Both figures show that the K_{JQ} values increase with temperature to a maximum between ambient temperature and 75°C and decrease again towards higher temperatures. Above ambient temperature the fracture toughness values, K_{JQ}, are ≥ 125 MPa√m. Such a behaviour of the initiation fracture toughness is also reported in the literature [4,7,8].

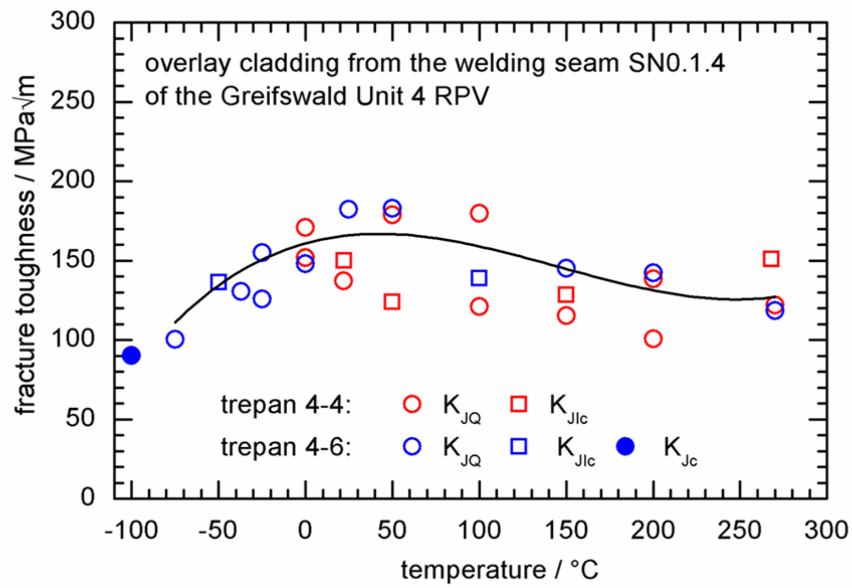

Fig. 5 Crack initiation fracture toughness values, K_{JQ}, vs. temperature of the investigated overlay cladding from the welding seam SN0.1.4. of the Greifswald Unit 4 RPV.

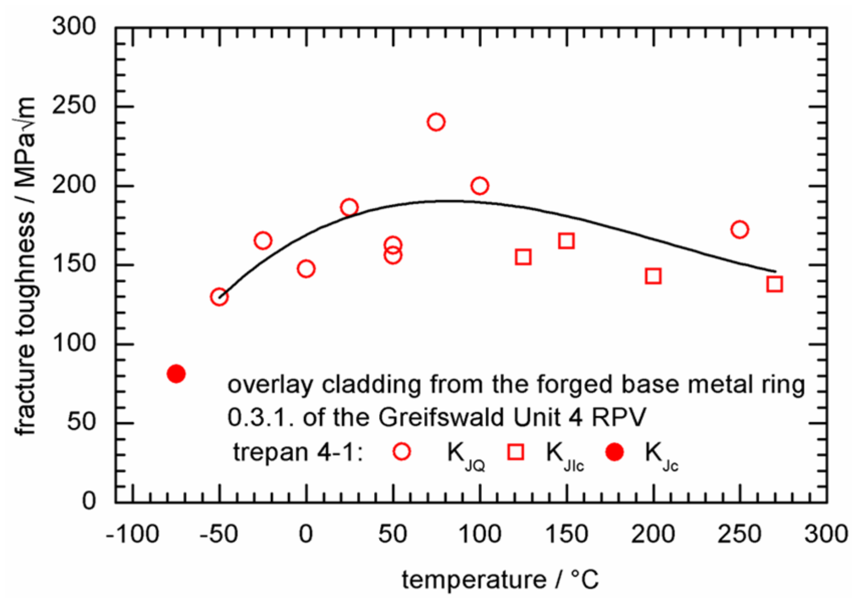

Fig. 6 Crack initiation fracture toughness values, K_{JQ}, vs. temperature of the investigated cladding from the forged base metal ring 0.3.1. of the Greifswald Unit 4 RPV.

At ambient temperature K_{JQ} values of 165 MPa√m and 179 MPa√m were approximated for the overlay cladding from the welding seam and the forged ring, respectively. The specimens from the cladding of trepans 4-1 and 4-6 fail unstably at -75°C and -100°C, respectively. Some specimens showed crack jumps or unstable failure after ductile crack extension within the 0.15 mm and 1.5 mm exclusion lines. In this case only data up to the crack jumps were used to fit the power law regression line.

As shown in Figs. 5 and 6, low K_{JQ} values were determined on specimens tested at 270°C, which is about the inlet water temperature of the WWER-440 reactors. At this test temperature the span of the K_{JQ} values reaches from 117 to 170 MPa√m, in which the lower values were measured on the specimens from the overlay cladding of the welding seam SN0.1.4. The scatter is caused by the accuracy of the load and COD measurement and in addition by the tearing strength of the non-homogenous cladding structure in the vicinity of the crack tip.

5. Summary and conclusions

- It could be shown that the initiation fracture toughness values, K_{JQ}, exhibit a maximum in the temperature range between ambient temperature and 75°C.
- The significant scatter of the K_{JQ} values is caused by the non-homogenous structure of the cladding with major differences in the tearing strength and uncertainties of the UC measurement.
- Crack jumps and unstable failure were found after 1 mm ductile crack extension above ambient temperatures and below -50°C, respectively.
- Above ambient temperature the lowest initial fracture toughness values, K_{JQ}, were determined with about 125 MPa√m for both the 1st and 2nd layer of the overlay cladding. These values are above the stress intensity factors estimated for a postulated surface crack in the overlay cladding during a PTS transient.
- It can be stated that the overlay cladding of the Greifswald Unit 4 RPV would remain intact and improves the integrity of the RPV after the operation up to 25% of the designed neutron loading for 30 full power years.

References

[1] Brumovsky, M.; Novosad, P.; Vacek, M.: Cladding Properties Changes During Operation. Proceedings of the IAEA specialists' meeting on irradiation effects and mitigation, Vladimir, Russia 15-19 September, 1997, IWG-LMNPP-92/2, IAEA, Vienna, Austria, 1997.

[2] Gillemot, F., Horvath, M., Uri, G., Fekete, T., Houndeffo, E., Acosta, B., Debarberis, L.; Viehrig, H.-W.: Radiation stability of WWER RPV cladding materials. International Journal of Pressure Vessels and Piping 84 (2007)8, pp. 469-474.

[3] Brumovsky, M.: Unified procedure for lifetime assessment of components and piping in WWER NPPs “VERLIFE”. Technical report, European Comission, 5th Euratom framework programme 1998-2003, Brussels 2003.

[4] Haggag, F.M., Corwin, W.R., Nanstad R.K.: Effects of irradiation on the fracture properties of steel weld overlay cladding. Nuclear Engineering and Design 124 (1990) pp. 129-141.

[5] Altstadt, E., Abendroth, M.: Fracture mechanical investigation of a thermo shock scenario for a VVER-440 RPV. Proceedings of the 34th MPA-Seminar, 09.-10.10.2008, Stuttgart, Deutschland.

[6] Abendroth M, Altstadt E: Fracture mechanical analysis of a thermal shock scenario for a VVER-440 RPV, Scientific technical reports of Forschungszentrum Dresden-Rossendorf FZD-474 ISSN 1437-322X, June 2007.

[7] Margolin, B.Z. et al.: TAREG 2.01/03 Neutron irradiation embrittlement assessment and validation of embrittlement models for WWER RPVs – Task 6: Investigation regarding cladding metal properties. European Commission, Brussels, Belgium, 2010.

[8] Timofeev,B.T., Karzov, G.P.: Assessment of the WWER-440/V-213 reactor condition. International Journal of Pressure Vessels and Piping, Volume 83(2006), Issue 3, pp. 216-226.

[9] Alekseenkov, N. N., Amaev, A., Gorynin, I., Nikolaev, V.A.: Radiation Damage of Nuclear Power Plant Vessel Steels. American Nuclear Society, La Grange Park, Illinois, USA, 1997.

[10] Viehrig, H.-W., Altstadt, E., Houska, M., Valo, M.: Fracture mechanics characterisation of the beltline welding seam of the decommissioned WWER-440 reactor pressure vessels of nuclear power plant Greifswald Unit 4, International Journal of Pressure Vessels and Piping 89(2012), 129-136.

[11] Viehrig, H.-W. Houska, M., Altstadt, E., Kuechler, R.: Fracture mechanics characterisation of forged base metal ring of the decommissioned reactor pressure vessel of NPP Greifswald WWER-440 unit 4. Journal of ASTM International (2012).

[12] Rindelhardt U., Viehrig H.-W., Konheiser J., Schuhknecht J., Noack K., Gleisberg B., “RPV material investigations of the former VVER-440 Greifswald NPP”, Nuclear Engineering and Design Vol. 239, No. 5, 2009, pp. 1581-1590.