CORROSION AND LOCALISED CORROSION INITIATION OF UNIRRADIATED AND ION IRRADIATED STAINLESS STEELS IN B-LI COORDINATED WATER CHEMISTRIES

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Nuclear fusion experimental facilities like Divertor Tokamak Test (DTT) Facility[1], Japan Torus-60 Super Advanced (JT60-SA)[2] and Korea Superconducting Tokamak Advanced Research (KSTAR)[3] require the use of borated water as a neutronic shielding medium in the Vacuum Vessel cooling circuits. Borated water in these nuclear fusion facilities is used at high enrichment, up to 95% ^{10}B, and high concentration, 8000 ppm B for DTT and 13400 ppm for KSTAR and JT60SA, compared to pressurized water reactors (PWRs) plants usually requiring ≤2400 ppm B (naturally enriched or enriched to 40 % in ^{10}B when enriched boric acid regime is pursued). The use of stainless steels in the nuclear industry has enabled the reliable operation of nuclear power plants for decades, however, 316L steels are not immune to corrosion[4] and stress corrosion cracking (SCC)[5],[6].

In this work corrosion of 316L and 316LN-IG steels exposed to highly concentrated borated water (8000 ppm B, pH_{80C}< 3.7[7],[8]) and borated water with addition of 5.7 or 57 ppm Li (as LiOH) relevant to experimental nuclear fusion cooling circuits were tested. The addition of a base, in this case LiOH, was here tested with the aim to optimise nuclear fusion cooling circuit water chemistry by increasing borated water pH following best practices gained during operation of the light water reactors (LWRs) fleet [9].

In this work, general corrosion and localised corrosion initiation analyses were tested using non-conventional small scale techniques. Small scale testing allows to test general corrosion and SCC initiation of ion irradiated specimens thanks to the low sampling volume and shallow area needed. Tests were performed on unirradiated and heavy ion irradiated 316LN-IG samples to understand the effect of irradiation on SCC initiation using non-conventional techniques. Heavy ion irradiation, using Ni ions, was chosen to reach high dose in a relatively low time compared to other type of ion irradiation (e.g. proton) without inducing samples radioactivity [10]. Ion irradiation was used as a surrogate, in an effort to simulate the effect of neutron irradiations and test, thanks to small scale techniques, complex phenomena such as irradiation assisted stress corrosion cracking (IASCC) tendency, as a proof of concept. Details of experimental procedure used to assess general corrosion can be found in Gasparrini et al.[8] and details of SCC initiation microcapillary testing can be found in [11]. Ion irradiated samples

were exposed to a damage up to 3 dpa, the threshold generally considered to be relevant for the phenomenon of IASCC (3 dpa and temperatures >260 °C [12]) using a source of 2 MeV Ni ions, fluence of $3e^{15}$ ions/cm^2 performed in ANTARES (Australian National Tandem Research Accelerator), ANSTO.

General corrosion from stainless steels was investigated using metal release experiments, after the first week of exposure, higher release of Fe and Ni were measured from the ion irradiated 316LN-IG samples compared to the unirradiated ones both passivated and exposed to 8000 ppm B at 80 °C. Results are shown in Figure 1.

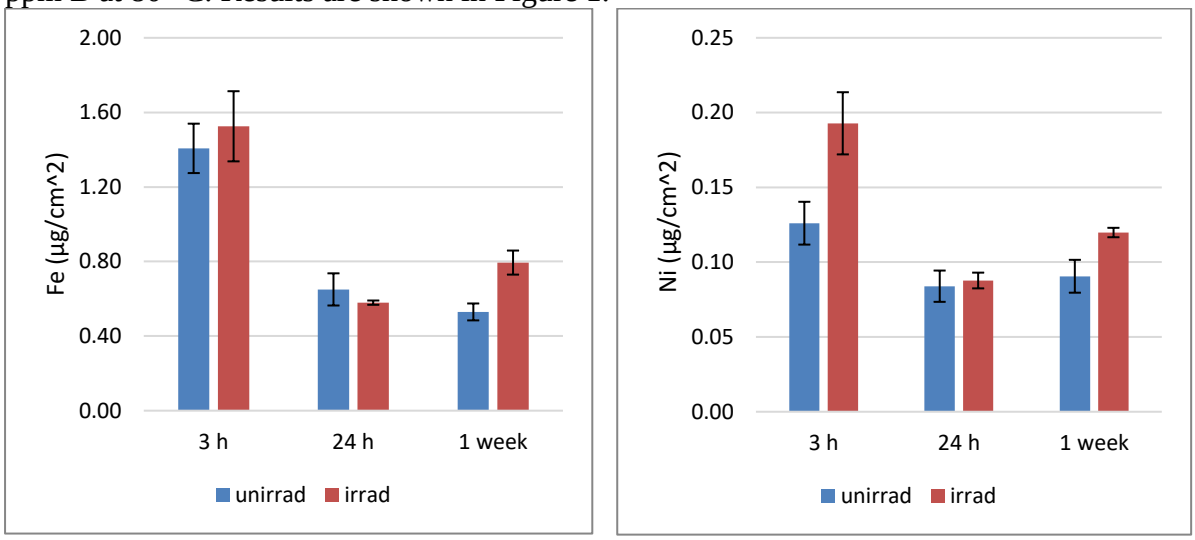

FIG. 1. Released metals (Fe and Ni) per surface area (µg.cm^{-2}) from 316LN-IG samples passivated for 12 weeks in borated water (8000 ppm B) at 80 °C: comparison of releases between unirradiated and Ni ion irradiated samples. Trace metal analyses quantified during sampling after 3 h, 24 h and 7 days. Error bars represent standard deviation from 6 measurements.

Results shown in Figure 1 highlight that after 1 week exposure both Fe and Ni releases were larger from the ion irradiated samples than unirradiated. Higher releases of Ni during first sampling (after the first 3 hours of exposure) were detected; this may be related to Ni ions implanted in the samples during ion irradiation (concentration from first 50 nm was estimated to be approximately 1-3 ppm from SRIM/TRIM simulations). Higher releases of Fe from ion irradiated samples were measured after 7 days exposure and onwards compared to unirradiated ones. Higher releases could be related to a less efficient passive layer grown on ion irradiated samples compared to unirradiated ones. In previous work using the same technique, higher releases were observed on samples with a less efficient passive oxide, which was characterised by scanning transmission electron microscopy-electron energy loss spectroscopy (STEM-EELS) and atom probe tomography (APT), on samples exposed to 8000 ppm B compared to samples exposed to ultrapure water.

To assess the susceptibility of localized corrosion initiation of unirradiated and ion irradiated 316LN-IG samples a microcapillary electrochemical technique was used[11]. Results, shown in Figure 2, showed that ion irradiated samples presented a lower localized corrosion resistance compared to unirradiated samples. Potentiodynamic and galvanostatic measurements revealed higher perturbations in the ion irradiated samples, indicating possibly lower integrity of the ion irradiated samples. Galvanostatic experiments showed a lower potential, suggesting reduced resistance of the passive layer due to the effect of ion irradiation.

From these experiments, using small scale techniques, it was observed that ion irradiated stainless steels, type 316LN-IG, exposed to highly concentrated borated water (8000 ppm B) were more prone to localised corrosion initiation compared to unirradiated steels.

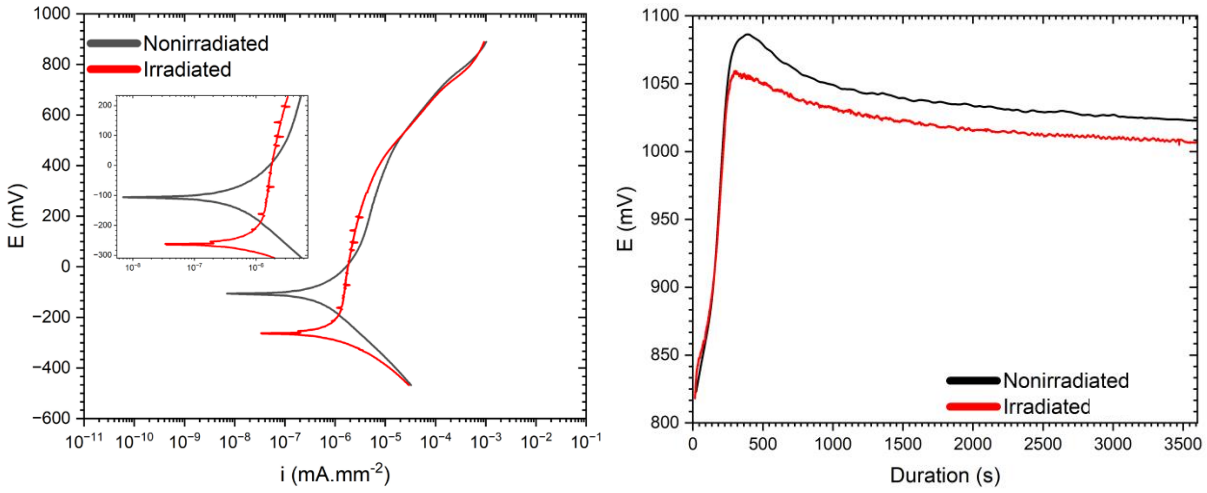

FIG. 2. Potentiodynamic (left) and galvanostatic (right) results of 316LN-IG samples passivated for 12 weeks in borated water (8000 ppm B) at 80 °C: unirradiated vs 2 MeV Ni ion irradiated

The need to optimise water chemistry in nuclear fusion cooling circuits requiring high concentration of boron (8000 ppm B) to reduce the tendency of localised corrosion initiation was investigated. To increase the pH of water (pH_{80C} > 4.5), the addition of LiOH was used. Metal release experiments were conducted on unirradiated samples in two water chemistries: 8000 ppm B additivated with either 5.7 or 57 ppm Li. Sampling was performed using the same procedure applied in Figure 1 and data for Fe and Ni in these two aqueous environments are shown in Figure 3.

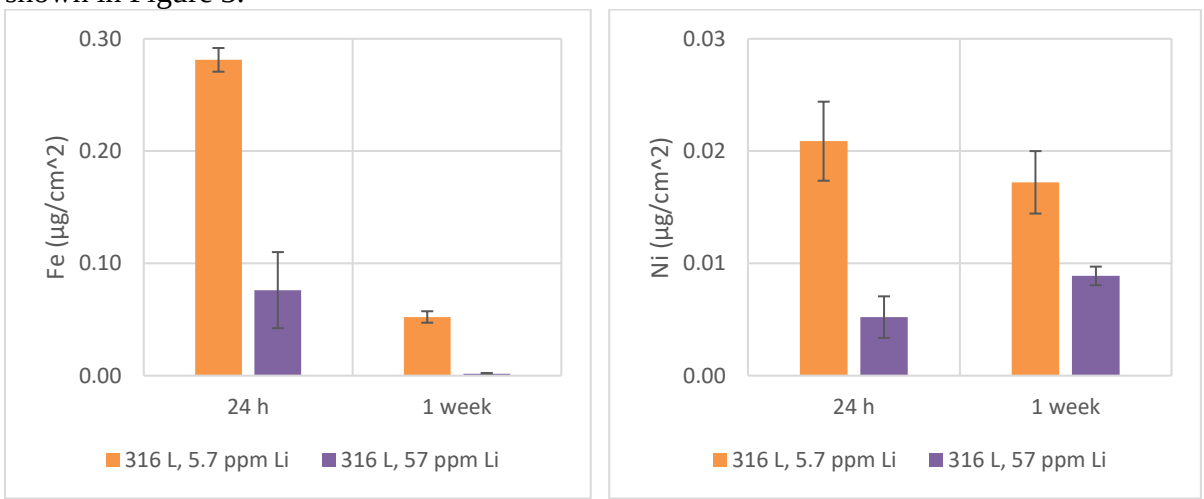

FIG. 3. Released metals (Fe and Ni) per surface area (µg.cm^{-2}) from 316L samples passivated for 12 weeks in borated water (8000 ppm B) at 80 °C with LiOH addition (5.7 ppm Li and 57 ppm Li). Trace metal analyses quantified during sampling after 24 h and 7 days. Error bars represent standard deviation from 6 measurements .

Metal releases from 316L drastically decreased when samples were exposed to the B-Li coordinated water chemistry tested compared to 8000 ppm B (compare results from Figure 1 and Figure 3). Fe and Ni releases from 316L in 8000 ppm B additivated with 57 ppm Li resulted in the lowest releases measured. The decrease in release for Ni was approximately 1 tenth when comparing results obtained in 5.7 ppm Li compared to 57 ppm Li. The addition of LiOH resulted in lowest releases, reducing general corrosion for these steels.

Small scale testing were shown in this work to allow in a timely manner for detection of the effect of irradiation, in this case ion irradiation, on complex phenomena such as localised corrosion initiation and general corrosion of 316L type steels exposed to different water chemistries relevant to nuclear fusion cooling circuits. The methodology and water chemistry chosen in this work relied on the knowledge obtained from operation of LWRs fleet. Further work is ongoing to reveal the effect of ion irradiation, inducing a damage of 3 dpa (the threshold for IASCC), on SCC susceptibility of 316LN-IG in 8000 ppm B by applying tensile loading during microcapillary testing.

REFERENCES

[1] R. Ambrosino, "DTT - Divertor Tokamak Test facility: A testbed for DEMO," Fusion Eng. Des., vol. 167, no. January, p. 112330, Jun. 2021.
[2] P. Barabaschi, Y. Kamada, H. Shirai, J. Integrated, and P. Team, "Progress of the JT-60SA project," 2019.
[3] G. Lee et al., "The KSTAR project: An advanced steady state superconducting tokamak experiment," Nucl. Fusion, vol. 40, no. 3Y, pp. 575–582, Mar. 2000.
[4] M. P. Ryan, D. E. Williams, R. J. Chater, B. M. Hutton, and D. S. McPhail, "Why stainless steel corrodes," Nature, vol. 415, no. 6873, pp. 770–774, 2002.
[5] INTERNATIONAL ATOMIC ENERGY AGENCY, "Stress corrosion cracking in light water reactors: good practices and lessons learned," IAEA Nucl. Energy Ser. NPT-T-3.13, 2011.
[6] EDF Stress Corrosion Cracking Operating Experience Discussion, Carol Moyer NRR/DNRL/NVIB, 2022
[7] E. Lo Piccolo, R. Torella, N. Terranova, L. Di Pace, C. Gasparrini, and M. Dalla Palma, "Preliminary assessment of cooling water chemistry for fusion power plants," Corrosion and Materials Degradation, vol. 2, no. 3, pp. 512–530, Aug. 2021, doi: 10.3390/cmd2030027.
[8] C. Gasparrini et al., "Water Chemistry in Fusion Cooling Systems: Borated Water for DTT Vacuum Vessel," IEEE Transactions on Plasma Science, pp. 1–5, 2022, doi: 10.1109/TPS.2022.3161185.
[9] INTERNATIONAL ATOMIC ENERGY AGENCY, "Coolant technology of water cooled reactors Volume 1: Chemistry of primary coolant in water cooled reactors", IAEA-TECDOC-667, 1992
[10] G. Was, "Challenges to the use of ion irradiation for emulating reactor irradiation", Journal of Materials Research, Vol. 30, No. 9, 14, 2015
[11] A. Yazdanpanah, et al. "Revealing the stress corrosion cracking initiation mechanism of alloy 718 prepared by laser powder bed fusion assessed by microcapillary method," Corros. Sci., vol. 208, 110642, 2022.
[12] V. Belous et al., "Assessment of the corrosion behaviour of structural materials in the water coolant of ITER", Journal of Nuclear Materials 258-263, 351-356, 1998