Post-Irradiation Tensile Properties of HT9 and FC92 Claddings Irradiated in BOR-60 up to 54.3 dpa and Comparison with Machine Learning Predictions

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1. Introduction

KAERI has developed FC92, a 9Cr–2W ferritic/martensitic (FM) steel cladding for sodium-cooled fast reactor (SFR) metal fuel. Its thermal creep resistance is superior to that of the reference HT9 cladding [1]. To qualify a new cladding, however, its in-pile behavior must be verified under fast-neutron irradiation.

For this purpose, HT9, FC92B, and FC92N (a nitrogen-adjusted variant) specimens were irradiated in the BOR-60 sodium-cooled fast reactor for about five years (2015–2020). Two test rigs containing tensile, pressurized creep, swelling, and microstructure specimens accumulated peak doses of up to 77.5 displacements per atom (dpa) at 600–650 °C (Table 1). The 357 irradiated specimens were transported to the hot cells of the Irradiated Materials Examination Facility (IMEF) at KAERI in 2024, and post-irradiation examination (PIE) is under way; room-temperature tensile tests of 18 specimens have been completed.

These specimens are all the more valuable because no fast-neutron irradiation facility is currently available for new test campaigns. Meanwhile, fast-spectrum reactors are actively being developed: the Natrium reactor under construction by TerraPower is an SFR-based small modular reactor, and the molten salt reactors being studied in Korea also operate on a fast spectrum. Licensing such reactors will inevitably require fast-neutron irradiation data on core materials. As the BOR-60 specimens are the only fast-neutron-irradiated cladding materials available in Korea, producing systematic background data through their PIE is of great importance.

In parallel, machine learning (ML) models were developed to predict the tensile properties of irradiated FM steels from 1,590 literature records. This paper presents the measured tensile properties of the BOR-60 claddings, compares them with the artificial intelligence (AI) predictions, and discusses the key factors governing the post-irradiation strength.

2. Experimental Procedure and Modeling

2.1 BOR-60 irradiation and tensile testing

Flat dog-bone tensile specimens (25.4 mm long with a 7.62-mm gauge) of the three alloys were irradiated in the two BOR-60 rigs summarized in Table 1. Because some specimens were replaced at interim inspections, the tested specimens cover six dose levels from 12.1 to 54.3 dpa at irradiation temperatures of about 600–650 °C.

The tests were performed at room temperature in the IMEF hot cell using a testing machine with remotely operated grips, one specimen per alloy at each dose level (18 in total). Elongation was obtained from the actuator displacement over the gauge length and cross-checked by remote length measurements before and after each test (Fig. 1).

Table 1. Summary of the BOR-60 irradiation campaign.

Item	MTR-1	MTR-2
Irradiation period	2015–2020	2014–2019
Days at power	1,213	1,113
Specimen temperature (°C)	≈580–611	≈601–655
Peak damage dose (dpa)	46.9 ± 6.0	77.5 ± 2.6

Fast fluence, E > 0.1 MeV (cm^{-2})	$(9.95 \pm 1.2)\times10^{22}$	$(15.7 \pm 0.4)\times10^{22}$

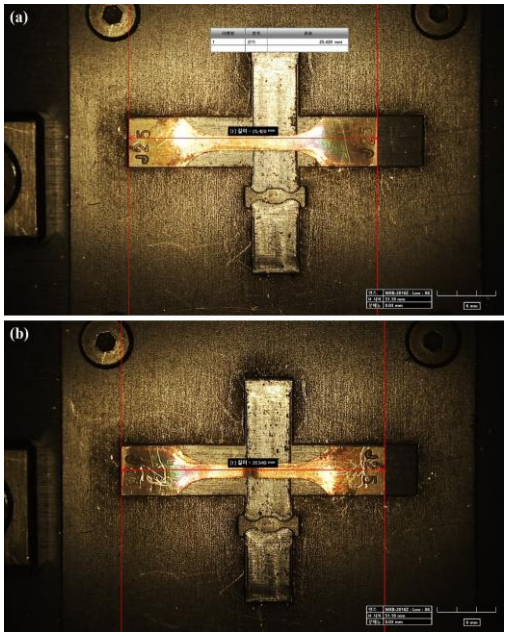


Fig. 1. Remote length measurement of an irradiated FC92B tensile specimen (J25) in the hot cell (a) before and (b) after the tensile test.

2.2 Machine learning modeling

A database of 1,590 tensile records of 9–12Cr FM steels was compiled from 69 references, each described by 27 variables covering the alloy composition, heat treatment, irradiation, and test conditions. Five regression algorithms were optimized with the Optuna framework [2] and evaluated by 10-fold cross-validation. An artificial neural network (ANN) was selected as the final model because it gives continuous, physically consistent predictions with coefficients of determination above 0.9 for the ultimate tensile strength (UTS), yield strength (YS), and total elongation (El). Prediction uncertainty was estimated by Monte Carlo dropout [3], and the contribution of each variable was quantified by the SHapley Additive exPlanations (SHAP) method [4].

3. Results and Discussion

3.1 Tensile properties of the irradiated claddings

Figure 2 shows the measured properties as a function of dose. Two features stand out. First, no irradiation hardening was observed: the YS of irradiated HT9 (521–691 MPa) remained at or below the unirradiated level, as did those of FC92B and FC92N. This contrasts with the strong hardening of FM steels irradiated below about 400 °C [5], and reflects the thermal recovery of irradiation-induced defects at the high irradiation temperatures of this campaign.

Second, the strength was governed by the irradiation temperature rather than the dose. At similar doses, the MTR-2 specimens (≈630–650 °C) were consistently weaker than the MTR-1 specimens (≈600–620 °C), and the highest strength of each alloy appeared in the batch irradiated at the lowest temperature (604 ± 13 °C).

All 18 specimens retained a total elongation above 13%; for FC92B and FC92N it even increased with dose, reaching 19.4% at 54.3 dpa. The FC92 claddings were 50–80 MPa softer and more ductile than HT9 at every dose, with no sign of embrittlement. All specimens fractured near the center of the gauge section (Fig. 1).

3.2 Comparison with AI predictions

The ANN model was validated against the BOR-60 results, which were not used for training. For the MTR-1 specimens, the maximum errors were 9.4% for UTS, 11.2% for YS, and 17.0% for El, i.e., an agreement of at least 88.8% for the strength properties. As shown in Fig. 3, the model reproduces the nearly dose-independent behavior of both HT9 and FC92B at an irradiation temperature of 606 °C.

The model further predicts that irradiation hardening saturates at 5–10 dpa at low irradiation temperatures and essentially vanishes above about 500–550 °C, consistent with the present measurements. SHAP analysis identified the irradiation temperature as a stronger contributor to the predicted YS than the dose, quantitatively supporting the temperature-dominated behavior observed in Section 3.1.

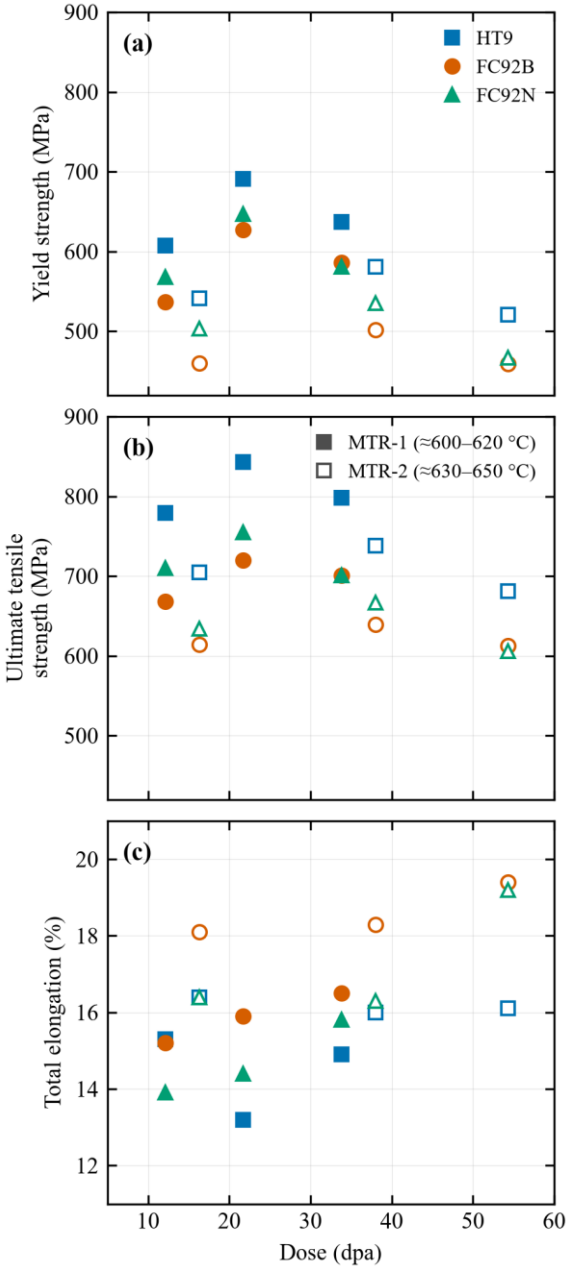


Fig. 2. Tensile properties of the irradiated claddings at room temperature: (a) yield strength, (b) ultimate tensile strength, and (c) total elongation.

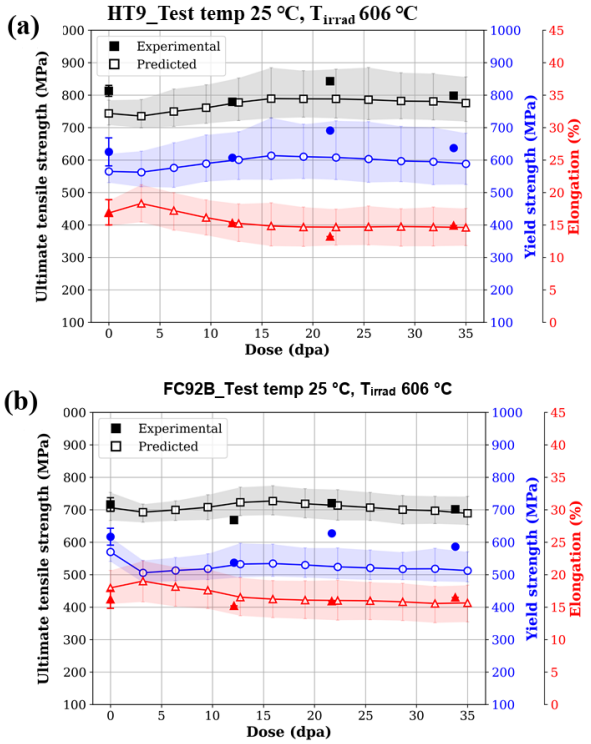


Fig. 3. Comparison of the AI predictions (open symbols with uncertainty bands) with the measured tensile properties (filled symbols) at 25 °C for (a) HT9 and (b) FC92B irradiated at 606 °C.

4. Summary and Future Work

Tensile tests of HT9, FC92B, and FC92N claddings irradiated in BOR-60 to 12.1–54.3 dpa at 600–650 °C showed no irradiation hardening or embrittlement. The strength was governed by the irradiation temperature rather than the dose, and every specimen retained an elongation above 13%. An AI model trained on 1,590 literature records reproduced the measured strengths within 11.2% and identified the irradiation temperature as the dominant variable.

To clarify the underlying mechanisms at the TEM scale, a KAERI–INL Lab-to-Lab joint research project on the PIE of the BOR-60 claddings was launched in 2026. Selected specimens, including stress-free tensile references and pressurized creep tubes, will be shipped to INL for advanced microstructural characterization, while elevated-temperature tensile tests (400 and 550 °C) proceed at KAERI. These data will provide a solid basis for licensing the FC92 cladding for high-burnup SFR fuels.

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