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[REGULAR POSTER TWIN] Effect of micro-alloying and heat treatment on the neutron irradiation behavior of EUROFER type steels

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The most problematic materials-related challenge for DEMO and future commercial fusion power plants concerns the mitigation of neutron damage, that is, embrittlement by irradiation-induced defects and helium as well as hydrogen transmutation. It has the highest impact on the design and licensing of blanket and divertor structures. As of today, the assumed design limits are highly speculative, even for a starting configuration with rather moderate performance. Presently available data on irradiation damage raise doubts on the feasibility of using EUROFER97 steel for a water-cooled starter blanket in a DEMO reactor since the ductile-brittle transition temperature (this transition temperature is called DBTT and defines the lower limit at which a material can be used in design to avoid brittle failure) increases significantly for irradiation temperatures below 350℃. The additional DBTT shift caused by transmutation (H and He production) can only be estimated based on a few results from one irradiation campaign with isotopically tailored EUROFER97 steel. In conservative calculations, it might be possible that the DBTT of EUROFER97 steel will exceed the operating temperature in water-cooled starter blankets within a relatively short time. However, the moderate heat transfer of He (as a coolant) will maintain the temperatures in the EUROFER97 structures at and above 350℃, which would guarantee moderate irradiation-induced DBTT shifts, especially in high dpa regions of the blanket like the first wall. Recent R&D points to the possibility to extend the high temperature operating limit of EUROFER97 to over 550 ℃ [1]–[3]. Albeit preliminary, these results if confirmed, would allow an increase in the outlet temperature of the coolant improving the reactor net efficiency [4]. Unfortunately, the improvement on the high-temperature end is often accompanied by an increase of the DBTT at the lower end, which might cause the same problems as described for the water-cooling design.

In summary, there are two DEMO blanket scenarios that cannot be assessed in full depth without further experimental data. After more than four years, the EUROfusion funded irradiation campaign LOT-IV, performed in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL), was recently completed. The objectives of LOT-IV were mainly addressing the above-mentioned DEMO related problems, but also included some further aspects (see also [5], [6]) as listed in the following:
- Can the EUROFER97 steel be tailored for water-cooled nuclear applications by modest changes of the chemical specifications, that is, by micro-alloying?
- How do specific thermo-mechanical treatments influence the irradiation behavior?
- Is it feasible to extend the upper operating temperature limit of EUROFER97 by a suitable heat treatment without increasing the irradiation-induced DBTT beyond the lower limit?
- Which strategies are promising? Which materials or approaches can be down-selected?
- Can the data produced by the applied small specimen test technology (SSTT) be correlated to data gathered from samples meeting international test standards?
- How does a technologically relevant heat treatment change the response to neutron irradiation? I.e. and in general, are there scaling issues?

The campaign included ten materials (for chemical composition see Table 1, the material conditions are listed in Table 2) that have been irradiated to a dose of 2.5 dpa at 300 ℃. For a meaningful assessment of the materials, the post-irradiation experiments were restricted to basic properties like hardness, tensile, and fracture mechanics tests combined with fractography and TEM analysis.

This paper presents and discusses results of the LOT-IV neutron irradiation campaign, which are relevant to the answering of the above-mentioned questions. So far, the results of the post-irradiation examinations might be preliminarily concluded as follows:
- Micro-alloying of EUROFER-type steels influences the mechanical properties. However, the effect is masked by the much stronger effect of heat treatment and fabrication history. A dominating impact on irradiation damage resistance cannot be clearly identified.
- Compared to available EUROFER97 data and compared to the reference material, specific thermo-mechanical treatment followed by a (more or less) typical heat treatment leads to significantly better DBTT (measured by T0) behavior for 5 alloys.
- At first glance, the extension of the upper operating temperature limit by an adjusted heat treatment seems to be successful.
- Most existing irradiation data were produced with the original EUROFER97 alloy. Now it seems that the newer alloys (EUROFER97/2 and 97/3 or most materials used in the LOT-IV campaign) show clearly improved

properties. This mirrors mainly in lower DBTT values.
- The applied strategies of removing manganese, reducing carbon, increasing vanadium and/or nitrogen as well as of performing thermo-mechanical treatments and/or heat treatments do not differ clearly enough to make a final assessment, yet.
- The only obvious choice for down-selection is material K (no manganese, very low carbon and reduced chromium content in combination with a very low final tempering temperature) that performed rather low in all aspects.
- A comparison of the basic mechanical test results with the unirradiated reference specimens shows that the applied SSTT is more sensitive to microstructural inhomogeneities, and therefore, compared to standardized (or bigger specimen sizes) leads to more conservative results.
- The effect of the non-optimized technological relevant heat treatment on material E is clearly recognizable in comparison to the other alloys. But compared to the EUROFER97 data, the measured DBTT shift and the irradiation hardening are both in the same range.

Most of these preliminary conclusions require independent confirmation by further examinations and/or other experiments. If confirmed, it most probably had a noticeable impact on materials technology and in-vessel component design.

Table 1: Chemical compositions (in wt. %) and notation of the steel variants irradiated in the LOT-IV campaign.

Table 2: Notation, planned application, and condition of the irradiated steel variants. AQ: air quenched, WQ: water quenched, AC: air cooled, LT: low temperature application (e.g. water-cooling in nuclear environment), HT: high temperature application (e.g. helium-cooled blankets), EF: EUROFER, TMT: thermo-mechanical treatment.

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