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Increasing irradiation and thermo-hydraulic performance of breeding blankets by ODS steel plating

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A significant part in the EUROfusion materials research programme is to tackle a fusion specific challenge: Neutrons produced by the fusion reaction damage materials by displacing atoms (displacement damage) and they transmute certain elements as well (transmutation damage). That is, on the one hand, materials are damaged by atom displacement, which mainly leads to hardening, embrittlement, aging, and accelerated creep. On the other hand, transmutation changes the chemical composition of materials. Therefore, helium bubbles form in steels, rhenium-osmium precipitations form in tungsten, and in most materials, hydrogen is produced, which leads to further material degradation. Without a special neutron source, like for example IFMIF/DONES, all these effects can so far only be simulated by neutron irradiation experiments in nuclear fission test reactors.

Nevertheless, even without detailed experimental data on high neutron dose effects it is clear that structural materials (i.e. EUROFER-type steels) will sooner or later come to an operating limit, in which the formation of helium bubbles reaches a critical amount and the material fails by embrittlement. Careful estimations put this limit to about 400-500 appm helium in 9%-Cr steels, which corresponds to neutron doses of 40-50 dpa in the surface area of the blanket first wall.

We have developed a strategy to mitigate this problem by the use of the following facts and assumptions:

- It is well known from neutronics calculations that the neutron dose decreases quickly inside the first wall. That is, not the whole blanket but only a plasma-near area is extremely loaded.
- Nanostructured oxide dispersion strengthened (ODS) steels (especially ferritic 14%-Cr ODS steels) seem to have an enormous trapping effect on helium. This suppresses especially the formation of large helium bubbles and could therefore significantly extend the operating limit of blankets.
- The only welding process that is applicable to ODS steels without restrictions is diffusion bonding. This has been demonstrated for several materials (even mixed material joints) and surface geometries.
- Compared to conventional steels, ODS steels show better irradiation behaviour in terms of tensile ductility. This has been proven by several irradiation campaigns.
- ODS steels typically have a much higher creep strength than conventional steels. It is assumed that this better behaviour is conserved also during neutron irradiation.

In summary, producing the plasma-facing, highly neutron and heat loaded part of blankets by an ODS steel, while using EUROFER97 for everything else, would improve the existing blanket designs significantly. It would allow a higher heat flux (due to the higher temperature limit of ODS steels) as well as a longer operating period (due to the higher helium concentration limit in ODS steels).

Beside elaborating the above-mentioned facts and assumptions in detail, we present in this paper all fabrication and production processes that are required to manufacture advanced DEMO blankets, i.e. only processes that can be performed on the industrial scale are considered. Due to the complex superposition of many different effects in a real component, single mechanical and physical materials tests (which are usually applied to characterize a new material) are not very meaningful in this case. Therefore, a test component (a so-called mockup, which in principle is a real component, but downsized to a representative limit) was fabricated using the same production processes and materials as for a real component. Finally, the mockup was tested in a "high heat flux test facility", which provides a coolant loop and a heat source that simulates the operating condition of a fusion reactor component. In our case it was the HELOKA test facility (Helium Loop Karlsruhe at KIT) which is equipped with an electron gun (details are given in [1], [2]).

The mockup fabrication included the following steps:

- Large-scale production (100 kg) of 14%-Cr ODS steel powder and fabrication of thin plates.
- Joining a EUROFER97/2 and an ODS steel plate by diffusion bonding.
- Machining the cooling channels by a long-wire electro-discharge machine which could also be used for real-size first wall parts.
- Tungsten-Inert-Gas welding manifolds and connectors to the cooling channels.
- Certify the ready mock-up for pressurized operation.

The next step consisted in the installation of the mock-up within the HELOKA test facility (see Fig. 1) which was followed by an extended high heat flux testing campaign. The operating temperature limit for EUROFER97 is 550 ℃. In the present test campaign this limit was finally exceeded by 100 K:

- 100 cycles @ 700 kW m-2 (~550℃ surface temperature)
- 100 cycles @ 800 kW m-2 (~600℃ surface temperature)

• 100 cycles @ 900 kW m-2 (~650℃ surface temperature)
• 7 x 2h long pulses @ 900 kW m-2 (~650℃ surface temperature)
After the tests were completed, the mock-up was removed and cut into several pieces for further inspections and for microstructure and defect analyses (see Figs. 2 and 3). So far, the results of the mock-up fabrication, the high heat flux test campaign, and the final analyses might be concluded as a fully successful project, which demonstrates that the use of ODS steel could make a big difference in the future performance of breeding blankets. Our paper also demonstrates that the topic "helium cooled high heat flux components"- as implemented in the EUROfusion WPMAT programme for advanced steels - involves multi-disciplinary R&D work (e.g. design, materials development and technology, simulation, large test facility engineering), is distributed over several institutes in different countries with a broad range of highly specialized infrastructure, and it is world-wide unique.

Figure 1: The ODS steel plated first wall mock-up as installed in the HELOKA facility.

Figure 2: Left: The mock-up after the high heat flux test campaign. The area within the rainbow-colored boarder was loaded by the electron beam. Right: The weld seam between the EUROFER97 body and the ODS steel plate is easily recognizable due to a remaining electron weld line, which was part of the diffusion bonding process.

Figure 3: After the high heat flux test campaign the mock-up was cut along several cross-sections for microstructure and defect analyses. The center cooling channel of the mock-up (the left channel in the photo) was intentionally placed nearer to the surface in order to simulate a massive production fault.

References
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