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QUALIFICATION AND TESTING OF MATERIALS AND COMPONENTS FOR APPLICATIONS IN FUSION

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1. ABSTRACT

The extremely harsh environment in future fusion reactors puts strong demands on the selection of materials and actively cooled in-vessel components in view of operational and economic requirements. Up to now, materials research in the field of thermonuclear fusion has been done primarily in laboratories and in test facilities that have focused on individual effects only, such as thermal fatigue, thermal shocks during transient events, plasma exposure, and neutron irradiation tests. Today, emphasis is also laid on synergistic effects such as high thermal loads under plasma exposure or the combination of thermal and neutron wall loads. This paper will give an overview of the work done in this field at Forschungszentrum Jülich during the last years.

2. INTRODUCTION

The plasma facing wall of future thermonuclear fusion reactors with magnetic confinement such as ITER or DEMO has to withstand harsh loading scenarios. These processes are associated with quasi-stationary thermal loads up to 20 MW/m^2 combined with short, extremely strong thermal transients up to the GW/m^2-range during unmitigated Edge Localized Modes (ELMs). In addition, irradiation effects resulting from the plasma species and the 14 MeV fusion neutrons have strong impact on the integrity of the wall armour materials. Therefore, also synergistic effects resulting from simultaneous thermal, plasma and neutron wall loads are evaluated in complex experiments. Under reactor-relevant conditions, thermally induced defects such as cracking and melting of the plasma facing material (PFM), thermal fatigue damage of the joints between the plasma facing material (PFM) and the heat sink of a plasma facing component (PFC), hydrogen-induced blistering and helium-generated formation of nano-sized tendrils at the plasma facing surface, and neutron induced damage formation and transmutation leading to a reduction of the thermal conductivity and embrittlement are the most serious damaging mechanisms. Today tungsten is considered as the most promising and reliable material for high heat flux components in future fusion reactors due to its high melting point (3410°C), low sputtering yield and a thermal conductivity of approx. 160 Wm^{-1}K^{-1}.

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3. METHDOLOGY

In order to address these loading conditions and to test and qualify PFM and PFC several test devices are operated at Forschungszentrum Jülich. In these tests, the versatility of electron beam test devices is used to combine steady state and transient heat loads in a single test device by the implementation of a rather complex beam scanning algorithm. In addition, the e-beam test device JUDITH 3, the follow up facility of JUDITH 1 that was operated for more than 25 years in a hot cell environment, is at the moment operated in a controlled area and should finally be installed as well inside a hot cell to perform High Heat Flux (HHF) tests on neutron irradiated materials and water cooled components. This unique device allows the high heat flux testing of pre-irradiated small material samples typically used for the investigation of the thermal-shock response on the one hand, and actively cooled wall components with, e.g. ITER or DEMO relevant geometries on the other hand. The larger test device JUDITH 2, still installed in a controlled area but outside of a hot cell, enables the testing of larger divertor targets with tungsten armour in fatigue mode, which can be, similar to JUDITH 3, combined with transient thermal loads simulating the ELM-loads with very high repetition rates up to 10^6 pulses or even higher. Synergistic experiments with simultaneous exposure of PFM under hydrogen/helium bombardment and laser beam transient thermal loads are realised in the linear plasma device PSI-2 and should be extended to the testing of neutron irradiated materials by setting up a new linear plasma facility in a hot cell adjacent to JUDITH 3.

4. RESULTS

The results described in this manuscript indicate that the material degradation is accelerated when synergistic effects are taken into consideration. Therefore, future experiments should also focus more thoroughly on synergistic effects. Multi-purpose test devices that enable simultaneous exposure with fusion relevant ion fluxes and thermal loading in-situ in a well diagnosed vacuum chamber are now available or must be adapted to the future needs for the fusion community. The integration of these high heat flux and plasma devices into a powerful neutron source with a fusion relevant energy spectrum would clearly go beyond technical and financial limits. Alternatively, test specimens (incl. miniaturized PFCs) must be irradiated in qualified neutron sources (material test reactors, spallation neutron sources or later in IFMIF/DONES) to be investigated in the above-mentioned multipurpose test devices located in dedicated hot cell laboratories. This is the only chance to approach these conditions, which allows generating data on synergistic loading conditions as input also for modelling to assess the performance and lifetime of future fusion reactors. The research, which is now going on, is primarily driven by magnetic confinement fusion activities; with the advancements now observed for inertial confinement fusion, transfer of knowledge is a prerequisite and potentially also adaptation of the testing facilities might be required.

5. CONCLUSIONS

ITER aims at demonstrating that sustainable thermo-nuclear fusion is feasible in magnetic confinement regimes and it should, beside other fusion devices like e.g. BEST, also act as test device for PFCs and PFMs under realistic synergistic loading scenarios that cover all the above-mentioned load types. In lack of such an integrated test device, today, material tests are being performed primarily in specialized facilities that focus mostly on the investigation of singular effects only, which is nevertheless essential as input for and validation of material modelling. New multi-purpose test facilities are now available which can also focus on more complex loading scenarios and thus help to minimize the risk of an unexpected material or component failure.