ADVANCED ENGINEERING MATERIALS
www.aem-journal.com

Fusion Materials Development at Forschungszentrum Jülich

Jan Willem Coenen

Material issues pose a significant challenge for the design of future fusion reactors. From a historic point of view, the material mix used for the first wall of a fusion reactor has continually evolved, from original steel vessels to carbon and other low-Z materials such as beryllium to tungsten as the primary candidate for a reactor's first wall armor and divertor material. For materials considered for fusion applications, a highly integrated approach is necessary. Resilience against neutron damage, good power exhaust, and oxidation resistance during accidental air ingress are design relevant issues while deciding on new materials or improving upon baseline materials. Neutron-induced effects, e.g., transmutation adding to embrittlement, retention, and changes to thermomechanical properties, are crucial to material performance. In this contribution, the recent progress (2013–2019) in fusion materials development for current and future fusion devices, at Forschungszentrum Jülich GmbH, with activities focussing on advanced materials and their characterization is given. It is a continuation and extension of the work given by Coenen et al.

1. Introduction

While considering a future fusion power plant multiple intertwined issues need to be evaluated. Some of the main problems a future reactor faces are linked to the materials exposed to the fusion environment and their lifetime considerations.[1–3]

The following interlinked issues arise: mechanical property evolution during operation, transmutation and neutron damage, ion impact and sputtering, thermal properties (after irradiation) related to steady-state heat loads and transient events, oxidation behavior during accidental air or water ingress, and the remaining issue of fuel permeation and diffusion.

This article is focussing on the contributions to the field made from one singular lab, work from other important contributors, partners, and research groups are acknowledged as part of the plenty-full citations and references in previous studies.[4,5]

In **Figure 1**, a rough sketch summarizing abilities and issues of tungsten is given. In the following sections, each of these will be described in detail.

In the interest of brevity and precision, the evolution of the general assumption to utilize mainly tungsten as first wall material will only be described in hindsight in Section 2.

In Section 3, several materials classes are being discussed. In Section 3.1, the issues of material activation and its influence on potential contingency needs for loss of coolant accidents are given. For the operational needs during high heat loads and high neutron fluxes, composites are being considered to facilitate better mechanical properties (Section 3.2). As W is mostly considered as armor material, especially with respect to blanket and first wall applications, technologies need to be developed to join a thin tungsten armor on top of the steel blanket material. Here, details on the issues and solution can be found in Section 3.3. For the efficient and safe operation of a fusion device, the safe use of tritium also needs to be considered. In Section 3.4, permeation barriers are being introduced as an essential part of the fuel management needed.

In the end, a brief summary of the solutions presented will be given followed by an outlook on how to integrate the given material solution into a component for a future fusion reactor.

2. From Carbon to Tungsten

Material development and studies in recent years have focussed on tungsten as the prime material candidate for fusion. Multiple devices have performed a change over from carbon fiber composites (CFCs) or graphite as their main first wall material. Here, the leading devices are Alcator CMOD[6–8] and Asdex Upgrade.[9–13] The reason behind that is manyfold; however, the main downside of using carbon or other possible low-Z plasma facing materials (PFM) is their strong erosion even under low plasma edge temperatures. This finally limits the lifetime and demands frequent component exchange. In addition, graphite shows a critical degradation under neutron impact leading to reduced thermal conductivity and anisotropic swelling.[14] The most crucial issue is, however, carbon–hydrogen codeposition and thus fuel retention.

Dr. J. W. Coenen
Institut für Energie und Klimaforschung
Forschungszentrum Jülich GmbH
52425 Jülich, Germany
E-mail: j.w.coenen@fz-juelich.de

Dr. J. W. Coenen
Department of Engineering Physics
University of Wisconsin–Madison
Madison, WI 53706, USA

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/adem.201901376.

DOI: 10.1002/adem.201901376

Jan W. Coenen has studied physics at RTWH Aachen, and did his doctorate at HHU Duesseldorf in 2006. He is the Project Leader Materials at IEK-4 since 2013 and Adjunct Professor of Engineering Physics at UW Madison since 2019.

This was elucidated in multiple publications[15,16] and shows, as schematically given in **Figure 2**, that processes such as codeposition of fuel can be one of the main limiting factors while operating, e.g., ITER, the next large experimental fusion reactor. Fuel retention based on codeposition increases linearly with particle fluence and can reach such large amounts that carbon is not permitted in the active phase of ITER and therefore basically excluded for future reactors due to its large issues related to retention.[15]

Fuel retention behavior of tungsten is subjected to previous and current studies. **Figure 3**a shows one of the most prominent results which lead to the exclusion of carbon from ITER. Studying retention behavior related to the original material combination for the nonactive phase for ITER consisting of plasma-facing components (PFCs)[19] made of Be for the first wall, CFCs for the divertor strike-line area, and W for the divertor baffle and dome area (Figure 3b), one can see that based on Figure 3a the retention is strongly increased due to codeposits of fuel with carbon.

The replacement of carbon[20,21] is driven by the requirement to remain within the safety limit for in-vessel tritium inventory. This means the long-term fuel retention. The latter is in carbon-dominated machines determined by codeposition of tritium with C which is transported stepwise to remote areas.[15,17] Instead of carbon as PFM, W is foreseen as in the divertor of ITER and tungsten-based alloys are the most promising candidates for PFCs in future reactors.[11]

To establish final proof experimentally that the replacement of CFC with W indeed gives the desired effect, the Joint European Torus (JET) was equipped with what is called the ITER-like wall (ILW):[22–28] a main wall made dominantly from beryllium and a full tungsten divertor. The main power bearing part is made from bulk tungsten and designed at Jülich.

It was shown that replacing CFC with W in the JET significantly reduces retention.[29]

Figure 4 shows for multiple operational scenarios that indeed by replacing the first wall and divertor with a full metal material mix, the retention can be reduced as expected from laboratory studies, modeling, and smaller scale device experiments. The studies related to fuel retention with the ILW show a strong reduction in the long-term retention rate between a factor of 10 and 20, depending on the confinement regime, in comparison with JET-C references. Results from the ILW are summarized in various papers and shall not be given in detail here.[29–35]

One issue for an all-metal device that has been studied in detail and shall not be given here apart from references is melting of PFCs. For an all-W ITER divertor, detailed studies have been performed and are given in refs. [36–41]. It was established that melting can and will be a potentially limiting factor and needs to be controlled by shaping and plasma control.[20,21]

In the following section, the material solutions for an all-W device shall be explored.

3. Materials for Fusion

In ref. [1], most of the problems for future fusion materials have been set out with links to the established roadmaps and assessments for fusion materials in existence at that time. Later, a short summary is given to show the development of materials and the systematic efforts undertaken as part of the material program at Forschungszentrum Jülich GmbH.

Materials programs as given in refs. [2,4,42–44] have already shown that the boundary conditions[45] to be fulfilled for the materials in a future reactor are in many cases above the currently understood technical boundaries. 1) Extended power handling, i.e., ability to withstand power loads close to 20 MW m^{-2}. Water cooling (low-temperature operation of the coolant: >150 °C) is the baseline option for the entire divertor system (PFCs and cassette body), whereas gas cooling (high-temperature operation of the coolant: >500 °C) is only regarded as a backup option subject to long-term development.[46] 2) The DEMO divertor will be exposed to an intense neutron irradiation. The peak dose is predicted to amount up to 6.5 dpa in the Cu tube and 2 dpa in the W armor per full power year (fpy).[47]

For materials related to the first wall and blanket, quite stringent requirements are also needed. 1) It is assumed that despite the radiation damage, erosion of the armor on the first wall is the dominant lifetime determining factor. Here, it needs to be considered that maximum thickness is also determined by the neutron transmission required for tritium breeding. 2) Even while starting up DEMO in phases, a final blanket could be required to withstand up to 50 dpa to minimize the exchange frequency, whereas a starter blanket might have to be exchanged already after 20 dpa.

For the next step devices, e.g., DEMO,[45,46,48–51] or a future fusion reactor including Chinese experimental fusion test reactor,[52] the limits on power exhaust, availability, and lifetime are even more demanding, as conventional monoblocks are allowing for 10 MW m^{-2},[20,21] and transmutation and radiation damage can quickly diminish the thermal conductivity to 50%.[53,54] Radiation effects including neutron embrittlement[55] do limit actively cooled W components in DEMO to about 3–5 MW m^{-2} due to the diminished thermal conductivity and the need to replace CuCrZr with steels with their low thermal conductivity.[45,56]

Quite extensive studies and materials programs[2,4,42,43] have already been performed. Based on these, it is assumed that the boundary conditions[45,46] to be fulfilled for the materials are in many cases above the technical feasibility limits as they are understood today. Here, new design criteria are also needed.[46,57–59]

In the following, we will, however, try to concentrate on three groups of issues and related new material classes. 1) *Tungsten armor on the first wall*: accident scenarios need to be considered, e.g., loss-of-coolant and air ingress (Section 3.1). 2) *First wall armor joints*: choose appropriate technologies for first wall materials joints of W—and Steels (functionally graded

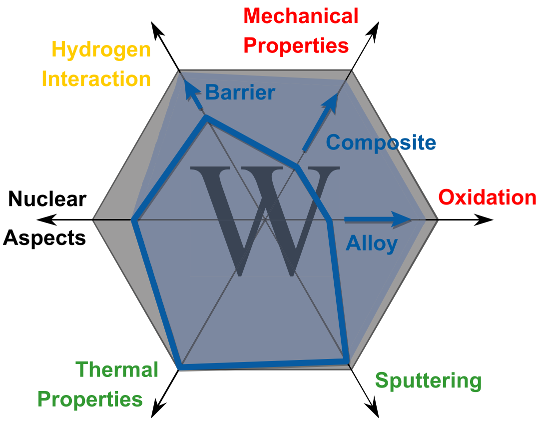

Figure 1. W as first wall and divertor material is still facing challenges. The blue lines give the status of performance with respect to ideal behavior, represented by the outline of the hexagon. The labels give the envisioned solutions and the colors the level of urgency from green to red. Nuclear aspects are discussed as part of each side and thus colored black.

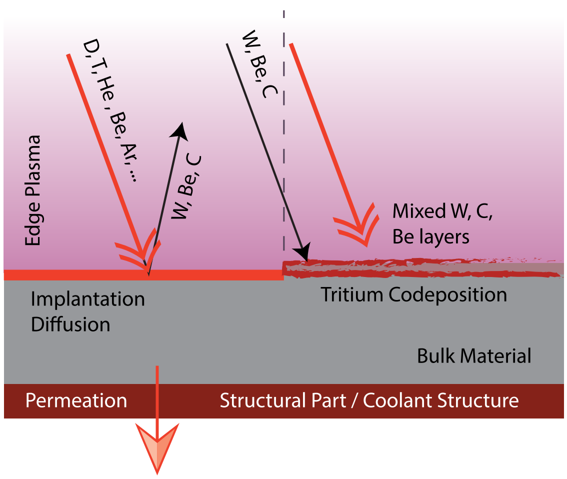

Figure 2. Fuel retention and permeation issues under plasma exposure conditions.

materials [FGMs] in Section 3.3). 3) *High heat flux materials*: effects of material degradation due to neutrons and high temperatures—generally embrittlement needs to be considered (Section 3.2). 4) *Tritium self-sufficiency and safety*: loss of tritium must be minimized (Section 3.4).

Even though the fusion materials program at Forschungszentrum Jülich GmbH covers a wide range of topics, new materials for fusion are being considered worldwide and also include new copper materials and copper composites,[60,61] tungsten heavy alloy and ductile phase toughened tungsten[62–64] as well as advanced manufacturing methods for even more advanced material concepts.[65,66]

3.1. W Alloys

As mentioned previously, W is the most promising candidate materials for the first wall. However, in case of a loss-of-coolant accident (LOCA), the temperature of the first wall armor made of W could rise up to 1450 K—due to nuclear after heat as shown in **Figure 5**.[67,68] In combination with influx of air, a break of vacuum or coolant, water, significant amounts of tungsten oxides WO_3 can be formed, which can be mobilized by sublimation at temperatures of about 1170 K. At the highest predicted temperatures of around 1450 K, a sublimation rate of 300 kg h^{-1} is calculated assuming a 1000 m^2 of first wall surface.[69]

In case of a reactor LOCA normally less than 50% of the elements typically found in the aerosols (such as Ag, Re, W, and so on) are actually released into the environment.[70]

To suppress the release of W oxides, tungsten-based alloys containing vitrifying components seem feasible, as they can be processed to thick protective coatings with reasonable thermal conductivity, e.g., by plasma spraying with subsequent densification as already demonstrated for titanium and tantalum coatings.[71] To suppress the release of W oxides, W-based self-passivating alloys were proposed by Koch and co-workers.[42,72,73]

As shown in **Figure 6**, a stable oxide scale would be formed in contrast to a volatile layer of W oxides. The crucial part of the materials development is now to establish what alloying elements can be used and are possible while also considering bulk production.

W–Si alloys showed good self-passivation properties by forming a SiO_2 film at the surface.[72] A compound of W–Si–Cr showed an even further reduction of the oxidation rate by a factor of 10^4 at 1273 K. However, the formation of brittle tungsten silicides was identified as unfeasible for mass production. In a next step, W–Cr–Ti was utilized and showed as well good oxidation suppression.[73]

Intensive studies on oxidation behavior, manufacturing, and mechanical properties were performed for both W–Cr–Si[74] and W–Cr–Ti,[75–78] and compared in previous studies.[79,80]

Enhanced erosion of light elements during regular reactor operation is not expected to be of concern as preferential sputtering of alloying elements leads to rapid depletion of the first atomic layers and leaves a pure W surface facing the plasma as per the given different sputtering yields.[81,82] Subsequently, the tungsten layer suppresses further erosion, hence utilizing its beneficial properties.

In the course of joint studies, a new composition W–Cr–Y[69,83] was proposed based on the existing results from the study by Telu et al.[84] Yttrium has the benefit of being a low activation material and shows high thermal stability as described previously. As before, model systems were produced by means of magnetron sputtering and tested with respect to the oxidation behavior.

So far, the most promising alloy systems feature Cr as a passivating element as well as small amounts of yttrium as an active element improving the oxidation resistance.

Y enhances the Cr transport toward component surface during oxidation; it adds to the stability of the oxide layer and supports the formation of a continuously growing, well-adhering, and dense Cr_2O_3 scale.[69]

Inclusion of an active element is thought to facilitate the formation of pegs, acting as a connection between the oxide and the alloy, as shown in **Figure 7**. In addition, active elements seem to alter the diffusion so that the oxide layer grows from the metal surface, avoiding pores. Active elements also can bond with impurities and thus allow a more pure oxide scale to grow leading to more efficient self-passivation.

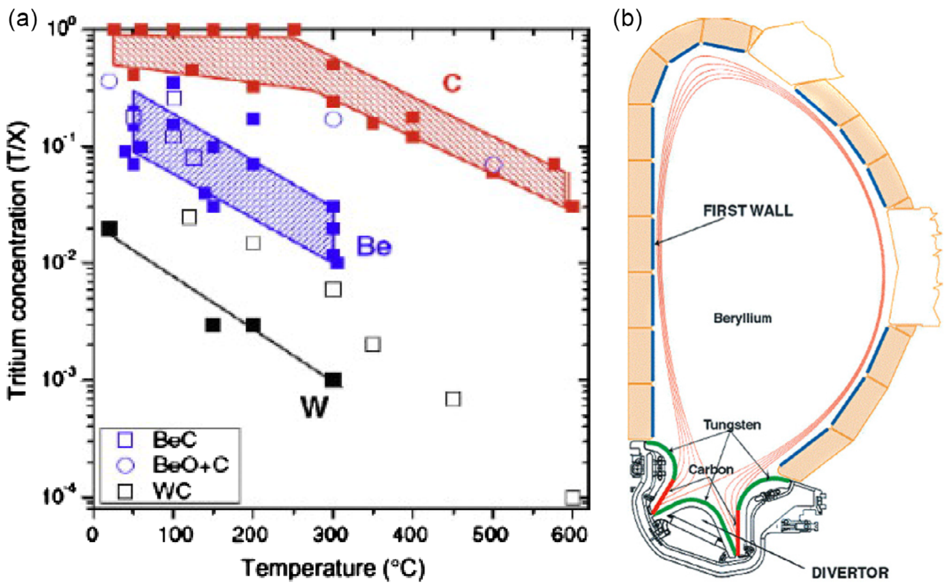

Figure 3. Overview on how material choices can influence the retention of D–T in future reactors. a) Retention fraction of T in codeposited C, Be, and W depending on temperature. Reproduced with permission[15,17] Copyright 2011, Elsevier. b) Original material mix for ITER incl. CFC at the strike point area. Reproduced with permission[18] Copyright 2011, Elsevier.

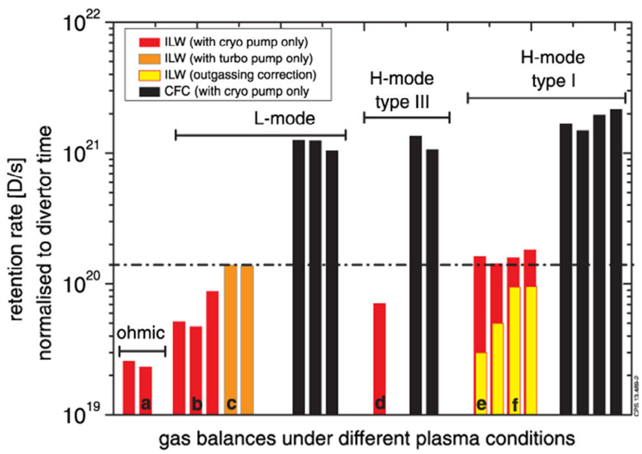

Figure 4. Measured D retention rates (logarithmic scale) for different plasma and confinement conditions in JET with the ILW and related to JET-C references. Reproduced with permission.[29] Copyright 2013, IOP.

In **Figure 8**, one of the main achievements is shown, the production of, and oxidation study on field-assisted sintering (FAST) produced, bulk W–Cr–Y samples.[85]

In ref. [85], it is stated that to achieve full passive safety it is required that the alloy maintains the protective oxide layer for several weeks to suppress sublimation. Thus, studies for passivation of up to 467 h were performed, as shown in Figure 8. One of the crucial aspects identified was also the necessity of quantifying not only the oxidation/mass gain but the direct measurement of the sublimiation of the oxides.[85,86]

It was shown that WCrY systems can suppress the oxidation rate significantly compared with that of pure W and have a much better performance than previous systems such W–Cr–Ti.[83,87–93]

In addition to the properties related to oxidation, the relevant studies also include the preparation for reactor deployment.[94] This means that the materials as available also need to be studied with respect to their plasma wall interaction (PWI) and erosion properties. Here, the study by Schmitz et al. is so far the only one which is available.[95] WCrY and W samples were simultaneously exposed to pure D plasma at relevant ion energies for DEMO[95,96] in the linear plasma device PSI-2; net erosion and surface recession were measured. Modeling with SDTrimSP including Cr diffusion was compared with experimental results. The SDTrimSP code (SD = static dynamic; SP = sequential and parallel processing) is a further development of TRIDYN with focus on low energy collisions and sputter processes.[97] For details, please refer to ref. [98].

The Cr-concentration gradients induced by preferential plasma sputtering obviates Cr diffusion. At sample temperatures of more than 600 °C and sputtering by D plus residual oxygen in the plasma ion flux, the Cr transport to the surface leads to enhanced erosion of the utilized W–Cr–Y samples at particles energy above the sputter threshold of tungsten. Considering the need for a long first wall, lifetime further studies are ongoing.

Main achievements in the area of W–Cr–Y are the inclusion of yttrium into the ternary systems[69,83] and the development of two main production routes: FAST[85] by the group at Forschungszentrum Jülich GmbH and hot isostatic pressing (HIP) at CEIT (Spain).[99,100] The detailed understanding of the underlying oxidation and sublimation mechanisms is also important.[85,86] A new system under consideration is currently W–Cr–Zr.[101,102]

The general need for self-passivating materials was identified early on and is embedded in a general effort to study and develop new solutions for materials in fusion reactors,[1,5,42] and hence has also lead to a wide international visibility.[103] For an integrated approach, combination with composite materials also ought to be considered.[104]

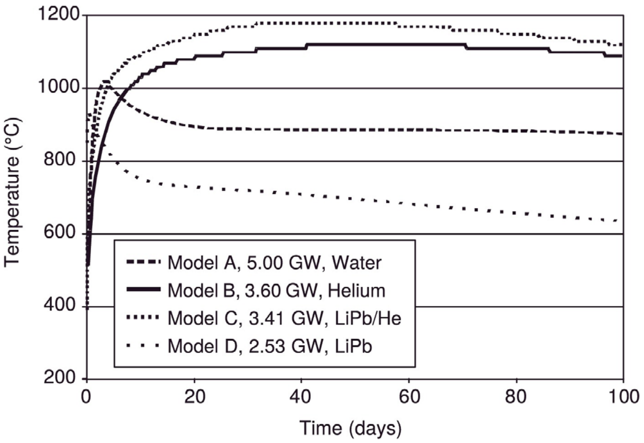

Figure 5. Calculated temperature profiles after an accident with a total loss of all coolant. Reproduced with permission.[67] Copyright 2007, EFDA, IOP.[68] Copyright 2006, EFDA, Elsevier.

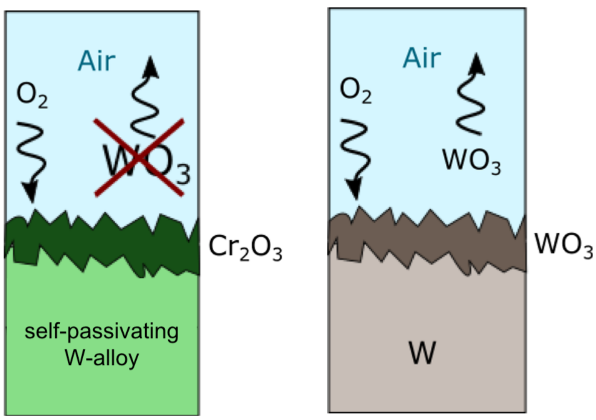

Figure 6. Self-passivation (*l*) compared with oxidation (*r*).

3.2. W Composites

To overcome the intrinsic brittleness and mechanical issues while using W as armor, a W-fiber-reinforced W composite material (W_f/W) incorporating extrinsic toughening mechanisms can be used, as shown in **Figure 9**.

Various production routes are available while considering components based on W_f/W composites; either chemical vapor deposition (CVD)[105,106] or powder metallurgical (PM) processes such as FAST[107,108] and HIP,[104,109–111] are available. As presented by Coenen et al.,[104] pressureless sintering of W_f/W was unsuccessful, as additional external pressure during sintering of W_f/W is required to get a dense and crack-free sample. The proof of principle for CVD and PM W_f/W has been achieved and was presented in multiple publications.[111–115] In the following, a short overview on the basic mechanisms and achievements will be given based on the PM production route initially developed at Forschungszentrum Jülich GmbH.[110,111,116–119]

Typical samples of CVD and PM W_f/W are shown in **Figure 10** where usual sizes are in the range of 40 mm × 40 mm × 5 mm or slightly larger for the CVD route.

Potassium-doped W fibers with 150 μm diameter and 2.4 mm length (OSRAM) together with pure W powders (OSRAM) (average particle size: 5 μm) were used as raw materials. These wires have been extensively characterized as to allow meaningful extrapolations.[120–125] Potassium-doped W wires will retain their ductility even at elevated temperatures (above 1500 K).[112] All pseudoductility mechanisms will thus remain activated.[104,111,113]

Properties of the fibers will degrade however due to various influences, e.g., by impurities during fabrication, high temperatures, or neutron irradiation during operation.[126,127] In ref. [128], it was found that all fiber samples categorized as brittle exhibit an increased C content compared with the fibers categorized as ductile.

All samples which are found to behave brittle have a C content of 0.0586 wt% compared with the ductile samples with lower than 0.0013 wt%. This was also found later in the W_f/W samples and found to be related to the carbon distribution in the samples.[115,129]

The short fibers used in this PM version of W_f/W are shown in **Figure 11**. Yttrium is used as the interface material to allow the energy dissipation mechanisms to become active. Without the interface, fiber and matrix would simple sinter together. Yttrium is an ideal candidate as the interface material for the W_f/W composite due to its several advanced properties: good thermal and chemical stability, high mechanical strength, and hardness.[104,116]

Studies to understand the pull-out of fibers include modeling.[130]

For the developed PM production of W_f/W, the homogenous introduction of powder between the fibers is required for good material properties; therefore, short fibers are used in contrast to,

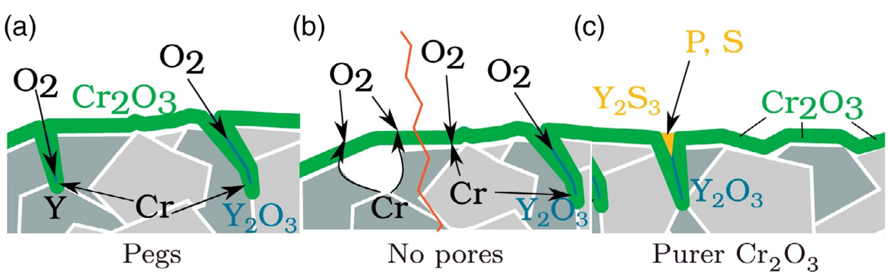

Figure 7. Functions of yttrium in changing the stability and performance of the oxide layer. a) Yttrium pegs are improving attachment of the oxide layer. b) Yttrium changes transport mechanisms through the oxide, avoiding of pores. c) Reaction of yttrium with impurities improves the purity of the Cr_2O_3 scale.

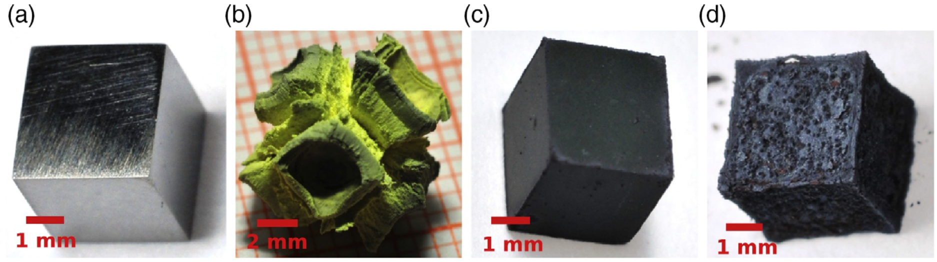

Figure 8. Photographs of the samples. a) W–Cr–Y alloy before oxidation, after grinding. An identical pure W sample is not shown as it looks identical. b) Pure W sample after 10 h of oxidation in synthetic air at 1273 K. c) Optimized W–Cr–Y alloy after 44 h of oxidation in synthetic air at 1273 K. d) W–Cr–Y alloy after 467 h of oxidation in synthetic air at 1273 K.[85]

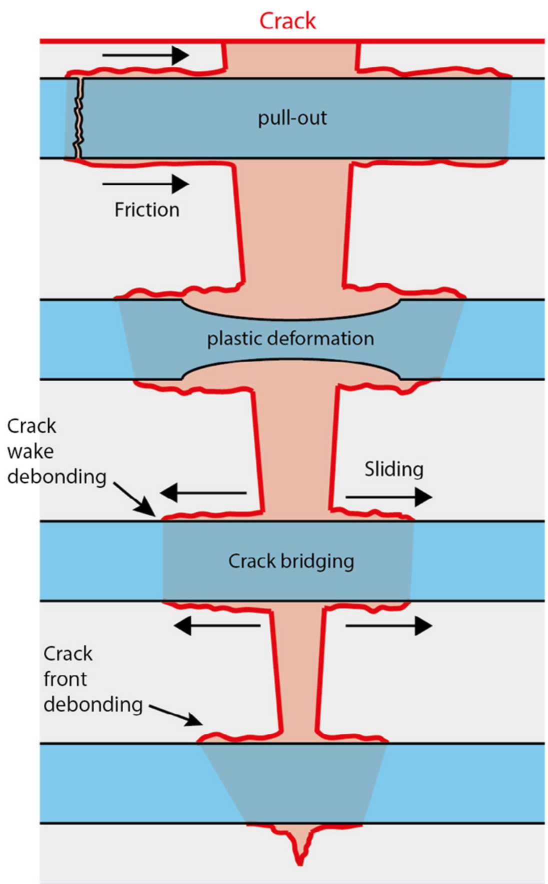

Figure 9. A selection of energy dissipation mechanisms in a fiber-composite material. Pull-out of fibers, pull-out of matrix elements, crack deflection at the interface, crack bridging by fibers, crack meandering at the interface, as well as plastic deformation of fibers.

e.g., woven preforms[131,132] or parallel long fibers as used in the CVD process route.[105,106]

The process gives rise to pressure and high temperatures on the interface and can thus cause a thin interface to dissipate.[133–135] Here, 2.5 μm-thick yttrium is applied for a viable interface similar to the work given by Mao et al.[111] The fibers and powders are mixed homogeneously before sintering, to produce a W_f/W sample with a random fiber distribution and orientation.

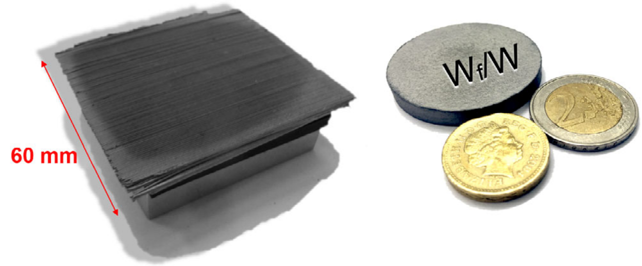

Figure 10. CVD W_f/W (*l*), PMW_f/W (*r*).

A density of ≈94% was achieved after applying the sintering process at 2173 K (4 min) and 60 MPa (heating rate 200 K min^{-1}).[104,111] In most production cases, a fiber volume fraction of 30% was used. However, variations thereof are used to understand the influence of interface, fiber, and matrix.

One of the crucial issues is to maintain as much of the properties[136] of the constituents even after exposing the material to the production cycle and the fusion environment. This allows for better extrinsic toughening and pseudoductile behavior. Here, mainly the weak interface and the strength of the fiber are important.[136] As the material should dissipate as much energy as possible, it is hoped to at least start with the inclusion of ductile fibers. Even if the fibers loose their ductility, the pull-out of fibers and the crack deflection can still deliver some pseudoductility for a viable material option. In the following, we will describe that one aspect of the production needs to be controlled with particular care to minimize the degradation of the material properties of the fibers.

One of the major improvements of the PM W_f/W samples established in the course of these studies was the role which the impurity content can play. In ref. [113,127], it was established that depending on the production mechanisms of the PM W_f/W, namely the choice of the die material, the properties do change from fibers becoming brittle to remaining ductile after production. In **Figure 12**, a sketch of the two different FAST procedures used is given. In one case, the powder and dye are separated by a graphite foil, whereas in the other case a thin tungsten foil is used. Based on FAST, samples with 20 and 40 mm diameter and a height of 5 mm were produced, as shown in Figure 10.

Typical tests for the materials not only include three- or four-point bending tests but also more advanced nondestructive tests.[137,138] From the bending test samples as given, e.g.,

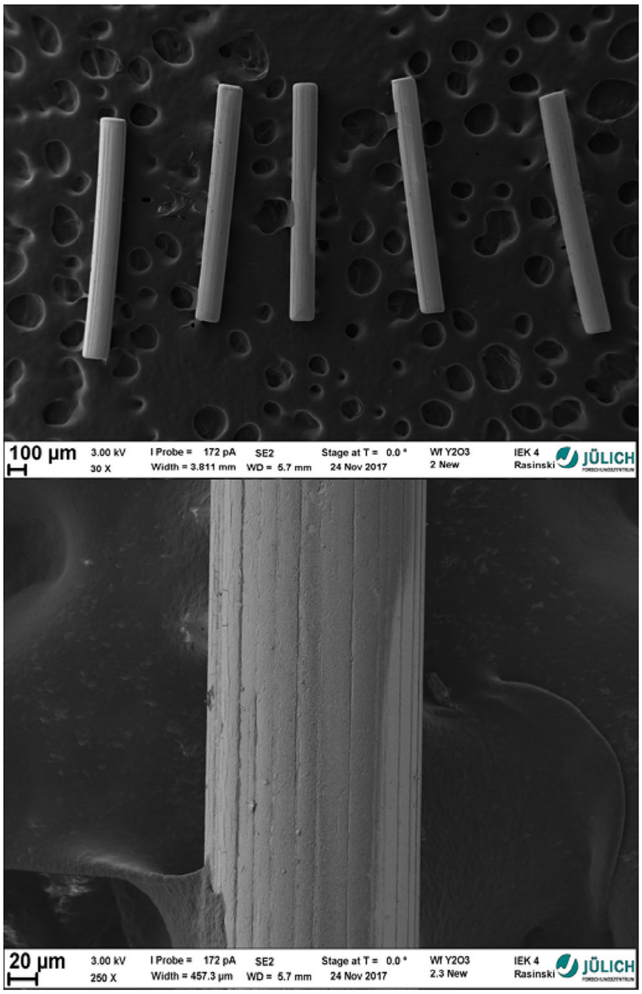

Figure 11. Short W fibers coated by 2.5 µm yttrium interface.

in **Figure 13**, one can clearly see fracture surfaces and thus the mechanisms at work required for pseudoductile behavior (cf., Figure 9).

For both PM W_f/W as well as CVD W_f/W, upscaling is crucial for further applications; thus, the development of larger scale material samples, mockups,[139] and their tests is an important part of the W_f/W development. For the PM W_f/W, upscaling is related to the application of FAST on larger scale material samples, and thus relatively straight forward. For the CVD route, multiple complications arise. From previous work including ref. [131] and modeling,[140] it is known that the choice of preform as well as deposition or infiltration process is crucial. Should one choose a layer-wise deposition process[105,106,113] for the production of the W_f/W composite one has to carefully adapt and choose the CVD parameters for proper densification[131,140] to allow full densification. The temperature as well as partial pressures are the rate determining properties.

To overcome the limitations of a layer-wise deposition, a continuous process was developed. For this process, a tungsten weave is continually rolled onto a copper tube and coated in situ with the W matrix. In general, it can be said that upscaling is the next big challenge for all types of W_f/W.

As a final remark on W_f/W, it also needs to be said that studies related to PWI are essential while applying new materials in the fusion environment; thus, the influence of the interface–fiber–matrix complex needs to be studied. The interfaces in the material and at the material surface can potentially influence fuel retention and erosion behavior significantly.[141] Yttrium among other characteristics is also used as a permeation barrier (see later).

3.3. W–Steel Joints

Having discussed tungsten as the main candidate for the PFMs of a fusion reactor, the joint to the underlying cooling structure or wall structure in general is crucial. From the differing thermal expansion coefficients for the different materials (copper: $\approx 16.5\ \mu m\ mK^{-1}$, tungsten: $\approx 4.5\ \mu m\ mK^{-1}$, stainless steel: $\approx 12\ \mu m\ mK^{-1}$), it is clear that a mature solution of joining them needs to be established. Thermally induced stresses and strains may either spontaneously or in the long-term yield premature failure of the FW component requiring feasible ways to reduce

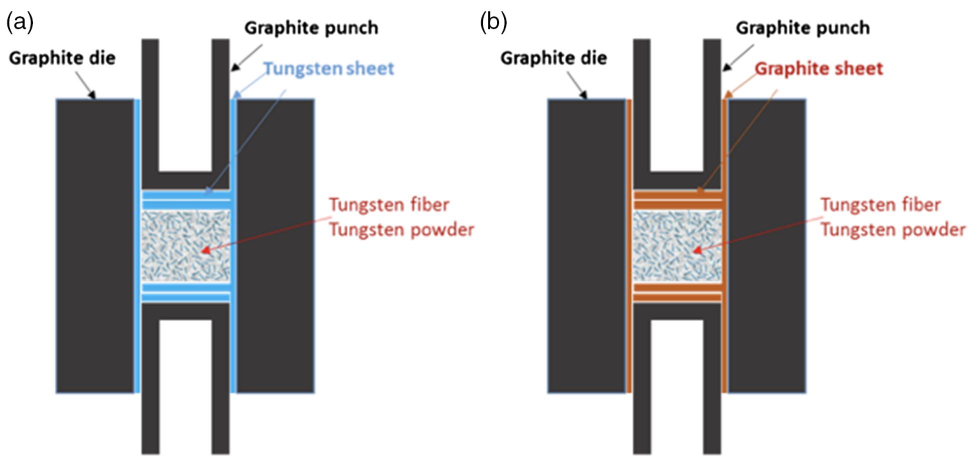

Figure 12. Two FAST procedures are used to facilitate understanding of carbon diffusion on the final material properties. a) Tungsten foil as diffusion barrier; b) graphite sheets for lubrication.

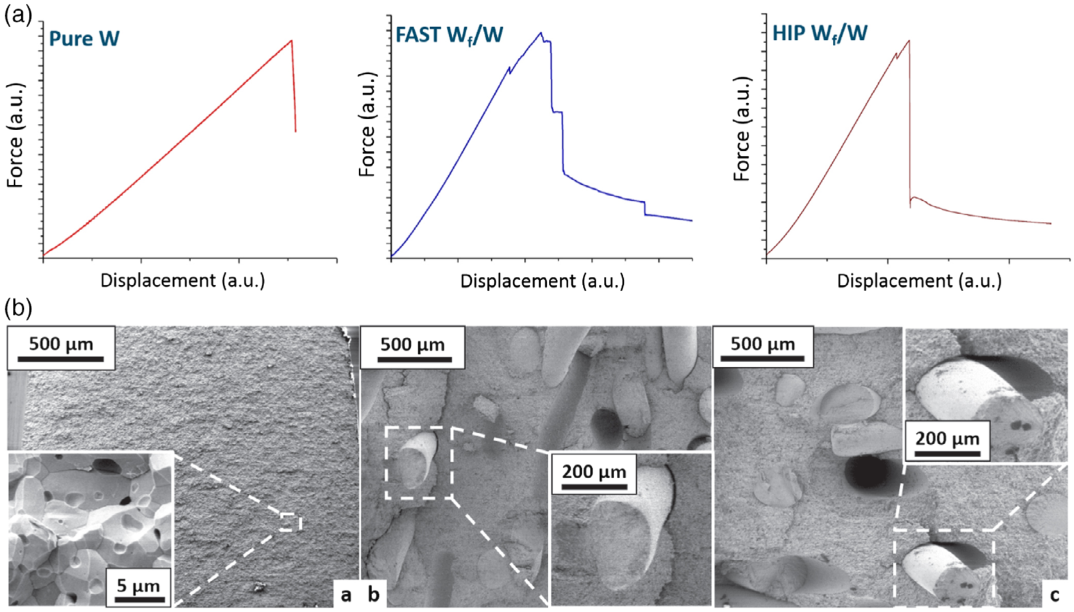

Figure 13. a) Force displacement curves in (a.u.) are given to compare the reletive behavior of pure tungsten, FAST and HIP W_f/W. b) The fracture surfaces in which the different energy dissipating mechanisms can be identified.

the loads.[142,143] Here, especially the high neutron capture cross-section and long cooling down time of tungsten, required before maintenance, is limiting tungsten armor at the first wall to a thin layer in the order of a few millimeter.[144]

As example systems for such armor layers, the development of FGMs between W as the PFM and the structural material, typically steel (EUROFER97), can be considered. As depicted in ref. [145], FGMs are promising candidates for interlayers between components of two different materials especially while considering applications such as the blanket modules of a DEMO[48,146] or even a helium cooled tungsten divertor with low-to-medium heat-flux (1–5 MW m^{-2}) for which the heat conductivity of EUROFER-97 may be sufficient.

For the production of W–steel FGMs typically PM routes are considered. Here, atmospheric and vacuum plasma spraying,[147,148] as well as resistive sintering technologies,[149,150] are relevant techniques. However, all current methods have problems with the formation of cracks or intermetallic phases (Fe_7W_6 and Fe_2W) due to extended high temperature exposure of the W–steel mixtures.

At Forschungszentrum Jülich GmbH, a new and unique production route for W–steel FGMs is being considered. The main new feature is the ultrafast sintering technique in addition to mechanical alloying allowing for the suppression of the brittle intermetallic phases.

The main focus of the activity is to establish if and how FGMs can be superior or comparable with classical joints. Here, modeling and production methods are considered together.[151–153] In addition to the ultrafast sintered FGMs,[154] atmospheric plasma spraying (APS) produced FGMs are also being studied.[155]

From modeling, the following was concluded: 1) an FGM is ideally composed of ten sublayers. Considering manufacturing aspects, three layers are however a good compromise, still keeping plastic deformations in the component at a minimum. 2) FGM thickness depends on the thermal loads expected. For lower heat loads, the stress-redistributing performance improves with thicker FGMs.

Electrodischarge sintering (EDS) is a uniquely short sintering technique[156] that was first used for the fabrication of Fe/W composites in ref. [154]. EDS combines characteristics of spark plasma sintering (SPS) and capacitor discharge welding. After mechanical alloying of the Fe and W powders, consolidation takes place within seconds. **Figure 14** displays the resultiung microstructure of the final FGM after the EDS process. The structure of the powders is typically stratified allowing for low or no production of intermetallics. The resulting properties of the FGM are summarized in **Figure 15** and are in line with the rule of mixture predictions.

In summary, 1) Fe/W composites shows little porosity and a fine distribution of Fe and W volumes. 2) With increasing W fraction, the Fe/W composites show a linear decrease in the coefficient of thermal expansion (CTE). 3) Albeit defects such as porosity and elemental interfaces, thermal conductivity of all composites is still above that of Fe/steel. 4) The mechanical parameters, e.g., yield strength, show an increase with increasing W fraction.

The work is currently moving toward utilizing EUROFER powders to produce even more relevant model-systems.

3.4. Permeation Barriers

One of the most prominent issues for fusion is fuel retention and management. Deuterium and tritium are the two hydrogen isotopes used. Tritium is a rare and radioactive isotope of hydrogen, and as such decays with a half life of roughly 12 years. Naturally occurring tritium is extremely rare on the Earth.

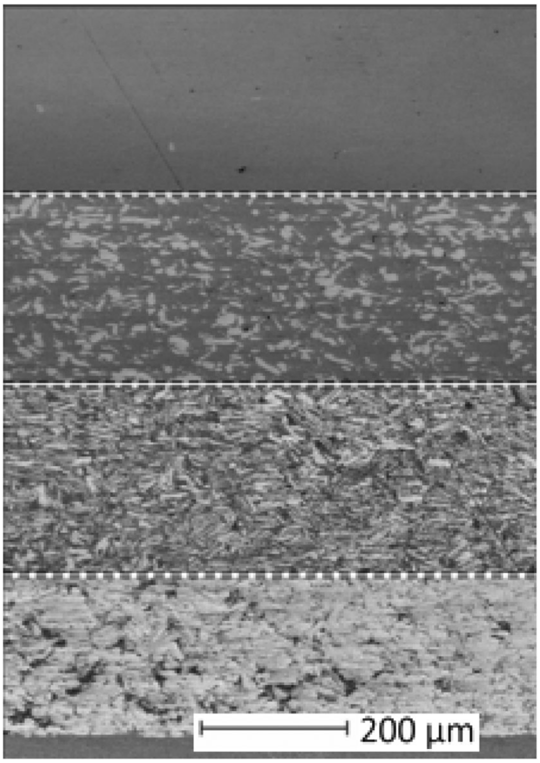

Figure 14. Microstructure of FGM produce via EDS. (Top to bottom) 100% Fe, 75% Fe, 50% Fe, and 25% Fe.

The atmosphere has only trace amounts, formed by the interaction of its gases with cosmic rays. It can be produced by irradiating lithium metal or lithium-bearing ceramic pebbles in a nuclear reactor.

For fusion applications, both the availability and safety aspects are important: the first one to maximize fuel efficiency and the later to minimize environmental impact. To reduce fuel loss and maximize inherent safety, tritium accumulation into reactor walls and permeation through walls have to be prevented. Therefore, the development of tritium permeation barriers (TPBs) is crucial for safe reactor operation.[157–159]

For a viable power plant, permeation barrier with a permeation reduction factor (PRF) in the range of 50–500 is necessary.[157,158] In general, the layers applied as TPBs have to feature high thermal and chemical stability in a reducing atmosphere. A lot of thin ceramic coatings, e.g., Er_2O_3 and Y_2O_3, fulfil these requirements.[160,161] In the past decades, Al_2O_3 and Er_2O_3 are among a large basket of material suitable as permeation barriers;[162,163] however, many of them show issues with respect to production and especially with stability under activation and activation itself.

At Forschungszentrum Jülich GmbH recently, Y_2O_3 is being considered as an ideal candidate for TPB material because of its favorably low activation behavior.[164] Studies on yttrium production, coating, as well as the analysis of the permeation behavior have been the corner stone of the activity. Based on a magnetron sputtering deposition process developed for Y_2O_3[116] studies on the permeation behavior of yttrium have lead to a significant breakthrough in the PRF as well as the understanding of the underlying microstructure.

For the determination of the PRF, a setup containing the sample between a high pressure volume (HPV) and a low pressure volume (LPV) is used as shown schematically in **Figure 16**. By varying pressure and temperature during the experiments, the various dependencies of the permeation process can be elucidated as described, e.g., by Engels et al.[165] Typically, the permeation process can be described as a combination of a surface or diffusion limited process, depending on surface properties and of the systems used.

For the initial studies, Y_2O_3 is deposited on both sides of mirror polished Eurofer97 steel substrates.[166] Before coating the samples, the substrate is cleaned by the magnetron plasma at lower energies. Then, additionally oxygen is injected into the

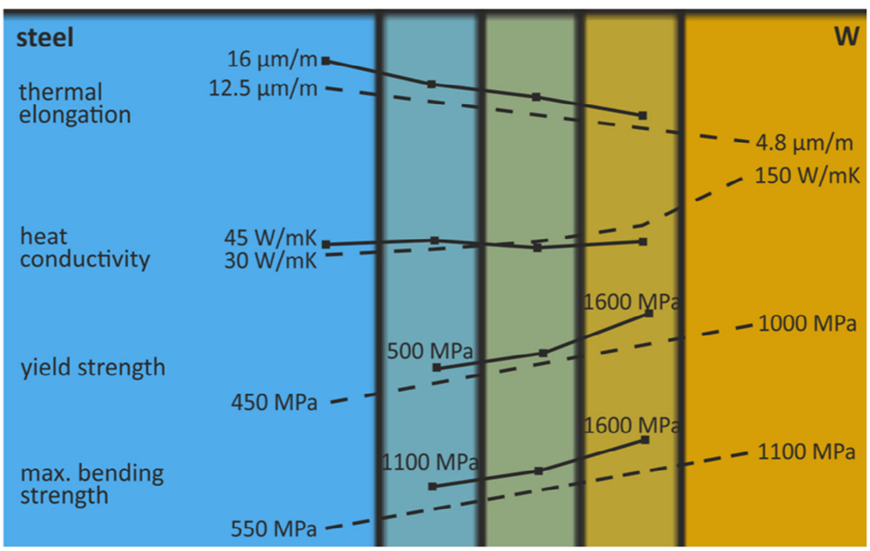

Figure 15. Rough sketch of thermomechanical properties of W/Iron FGMs based on the previous studies.[151,154]

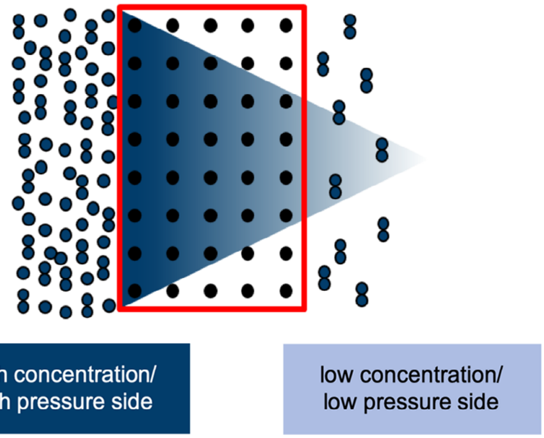

Figure 16. Schematic view of experimental setup for permeation rate determination.

chamber, and an yttrium metal target (Kurt J. Lesker Company) is sputtered.

Due to the reaction of gas with metal ions an Y_2O_3 thin film is formed. After the deposition, the roughly 1 μm thin films are annealed at 550 °C for 16 h in a vacuum furnace at a pressure to achieve the stable cubic phase structure of the Y_2O_3 system. For further studies, three different deposition modes were used. The hot metallic mode with substrate surface heating during the deposition process, the cold metallic mode without this surface heating, and the reacted mode also without this surface heating. Due to the higher resistance of the oxidized target, the deposition voltage in the reacted mode (<100 V) is lower than in the hot metallic mode (>300 V).[165] Dependent on the mode used, the mismatch of the CTE between steel and oxide ceramic can lead to cracking. To reduce the surface temperature differences between the deposition process and the subsequent experiments, the substrate surfaces are heated up to ≈300 °C for hot metallic mode.

In **Figure 17**, the three main types of microstructures produced are indicated and also related to their respective production process. Figure 17a,b mainly shows the difference between (hot) metallic mode and reactive mode, and Figure 17c also shows the option of a layered system.[165]

While considering the different coatings, one of the main outcomes of the studies at Forschungszentrum Jülich GmbH can be summarized as follows.

The PRF varies clearly with the microstructure of the coating in the order of up to a factor of 100.[165] Due to the difference in the coating process, control of the microstructure can be achieved, e.g., hot metallic versus reacted mode (Figure 17). The thin films grow in the reacted deposition mode in an equi-axed grain structure and in the hot metallic mode in a columnar grain structure. In the layer system, both grain structures can be found as one layer is based on the hot metallic and the other on the reacted mode. Annealing at 550 °C for 15 h leads to all samples showing the Y_2O_3 stoichiometry. This annealing step is essential to achieve the cubic phase of Y_2O_3.

For the three different samples, one can essentially identify a decrease in grain boundary densities in the permeation direction from highest to lowest: reacted mode, layer system, and hot metallic mode—this is essentially also the trend for the permeation flux. Consequently, the grain boundary diffusion through the Y_2O_3 thin films is preferred compared with bulk diffusion. For the reacted mode, a PRF of 24 and for the hot metallic mode a PRF of 1100 is determined. In addition to TPBs, the permeation behavior through pure steel and EUROFER97 samples was also measured.[167] In both cases, Eurofer97 and 316L, the permeation behavior is diffusion limited. The permeation through the 316L Steel is about a factor of ten smaller compared with EUROFER97. This is relevant in particular for consideration in ITER operation as no permeation barriers are so far considered.

For studies of other candidate materials, references related to an intensive collaboration with a Japanese group are given. Particularly erbia is considered in the subsequent section.[168–183]

4. Conclusions

The fusion materials research at Forschungszentrum Jülich GmbH is focussing on the materials related to the plasma

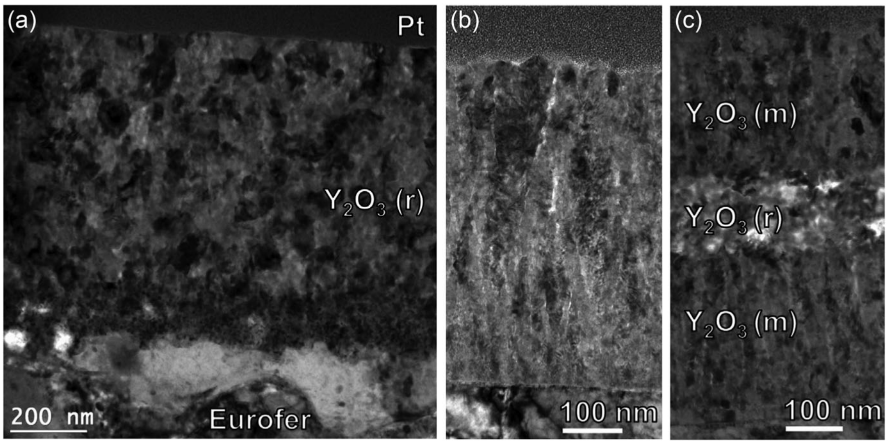

Figure 17. TEM images of the Y_2O_3 thin film cross sections after the permeation measurements of the a) reacted mode, b) the hot metallic mode, and c) the layer system on Eurofer. b,c) Pt is coated on the top of each thin film.

materials interface. This means the focus lies on tungsten, the joint to the structural material, as well as issues related to hydrogen interaction. Two areas that were not presented in this article are qualification of materials and diagnostic mirror, both staples of the materials research at Forschungszentrum Jülich. This is not an oversight because in parallel to this review on materials development two topical reviews on materials qualification as well as diagnostic mirrors by Jülich authors have been made available and thus can be considered as excellent sources. For materials qualification, refer to ref. [184] and sources there in, whereas for diagnostic mirrors please do consider.[185] For details on "Material testing facilities and programs for plasma-facing component," also refer to ref. [186].

In summary, it can be said that based on the current work new operational space can be gained by making tungsten more resilient to failure modes by utilizing a composite approach and allowing for passive safety by controlling potential oxidation behaviors by means of new tungsten alloys. The later is relevant in particular for the first wall and blanket area of a future fusion reactor while the composites due to their enhanced ductility, while retaining pure tungsten thermal properties, is typically considered for the load bearing components in the divertor.

In general, material for fusion needs to be considered in an integrated approach; thus, joints and functional layers need to be included in any component design, this is where FGMs as well as permeation barriers play an integral party to make PFCs viable for application. In future, the materials research at Forschungszentrum Jülich GmbH, related to fusion, will extend the activities with respect to industrial upscaling and component production and testing. Here, the focus will be the applicability in the medium-to-long term for a European Demo to be constructed in the 2040s. Material testing of those components will then be performed analogous to the activities described by Linke et al.[184] that successfully lead to the use and qualification of bulk baseline tungsten materials in ITER.

Acknowledgements

This work was conducted within the framework of the EUROfusion Consortium and received funding from the Euratom Research and Training Programme 2014–2018 and 2019–2020 under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. A special thank you goes to the whole community of materials researchers in Jülich, Germany and worldwide without which all of this work would not be possible.

Conflict of Interest

The author declares no conflict of interest.

Keywords

composites, fusion materials, tungsten

Received: November 11, 2019
Revised: February 19, 2020
Published online: April 13, 2020

[1] J. W. Coenen, S. Antusch, M. Aumann, W. Biel, J. Du, J. Engels, S. Heuer, A. Houben, T. Hoeschen, B. Jasper, F. Koch, J. Linke, A. Litnovsky, Y. Mao, R. Neu, G. Pintsuk, J. Riesch, M. Rasinski, J. Reiser, M. Rieth, A. Terra, B. Unterberg, T. Weber, T. Wegener, J.-H. You, Ch Linsmeier, *Phys. Scr.* **2016**, *2016*, 014002.
[2] D. Stork, P. Agostini, J. L. Boutard, D. Buckthorpe, E. Diegele, S. L. Dudarev, S. Gonzalez, A. Ibarra, C. Linsmeier, G. Marbach, B. Raj, *Assessment of the EU R&D Programme on DEMO Structural and High-Heat Flux Materials, Final Report of the Materials Assessment Group, Technical Report EFDA(12)52/7.2*, EFDA, **2012**.
[3] R. P. Wenninger, M. Bernert, T. Eich, E. Fable, G. Federici, A. Kallenbach, A. Loarte, C. Lowry, D. McDonald, R. Neu, T. Potterich, P. Schneider, B. Sieglin, G. Strohmayer, F. Reimold, M. Wischmeier, *Nucl. Fusion* **2014**, *54* 114003.
[4] D. Stork, P. Agostini, J. L. Boutard, D. Buckthorpe, E. Diegele, S. L. Dudarev, C. English, G. Federici, M. R. Gilbert, S. Gonzalez, A. Ibarra, C. Linsmeier, A. Li Puma, G. Marbach, P. F. Morris, L. W. Packer, B. L. Raj, M. Rieth, M. Q. Tran, D. J. Ward, S. J. Zinkle, *J. Nucl. Mater.* **2014**, *455*, 277.
[5] R. Neu, J. Riesch, J. W. Coenen, J. Brinkmann, A. Calvo, S. Elgeti, C. García-Rosales, H. Greuner, T. Hoeschen, G. Holzner, F. Klein, F. Koch, C. Linsmeier, A. Litnovsky, T. Wegener, S. Wurster, J.-H. You, *Fusion Eng. Des.* **2016**, *109–111*, 1046.
[6] B. Lipschultz, D. A. Pappas, B. LaBombard, J. E. Rice, D Smith, S. J. Wukitch, *Nucl. Fusion* **2001**, *41*, 585.
[7] I. H. Hutchinson, R. Boivin, F. Bombarda, P. Bonoli, S. Fairfax, C. Fiore, J. Goetz, S. Golovato, R. Granetz, M. Greenwald, S. Horne, A. Hubbard, J. Irby, B. LaBombard, B. Lipschultz, E. Marmar, G. McCracken, M. Porkolab, J. Rice, J. Snipes, Y. Takase, J. Terry, S. Wolfe, C. Christensen, D. Garnier, M. Graf, T. Hsu, T. Luke, M. May, A. Niemczewski, et al., *Phys. Plasmas* **1994**, *1*, 1511.
[8] B. Lipschultz, H. Becker, P. Bonoli, J. Coleman, C. Fiore, S. Golovato, R. Granetz, M. Greenwald, D. Gwinn, D. Humphries, I. Hutchinson, J. Irby, E. Marmar, D. B. Montgomery, F. Najmabadi, R. Parker, M. Porkolab, J. Rice, E. Sevillano, Y. Takase, J. Terry, R. Watterson, S. Wolfe, *J. Nucl. Mater.* **1989**, *162–164*, 793.
[9] R. Neu, K. Asmussen, K. Krieger, A. Thoma, H.-S. Bosch, S. Deschka, R. Dux, W. Engelhardt, C. Garca-Rosales, O. Gruber, A. Herrmann, A. Kallenbach, M. Kaufmann, V. Mertens, F. Ryter, V. Rohde, J. Roth, M. Sokoll, A. Stäbler, W. Suttrop, M. Weinlich, H. Zohm, M. Alexander, G. Becker, K. Behler, K. Behringer, R. Behrisch, A. Bergmann, M. Bessenrodt-Weberpals, M. Brambilla, et al., *Plasma Phys. Control. Fusion* **1996**, *38*, A165.
[10] R. Neu, A. Kallenbach, M. Balden, V. Bobkov, J. W. Coenen, R. Drube, R. Dux, H. Greuner, A. Herrmann, J. Hobirk, H. Haehnle, K. Krieger, M. Koaean, P. Lang, T. Lunt, H. Maier, M. Mayer, H. W. Mueller, S. Potzel, T. Puetterich, J. Rapp, V. Rohde, F. Ryter, P. A. Schneider, J. Schweinzer, M. Sertoli, J. Stober, W. Suttrop, K. Sugiyama, G. van Rooij, et al., *J. Nucl. Mater.*, *438*:S34, **2013**.
[11] R. Neu, ASDEX Upgrade Team, EU PWI Taskforce, JET EFDA Contributors, *Plasma Phys. Controlled Fusion* **2011**, *53*, 124040.
[12] R. L. Neu, *IEEE Trans. Plasma Sci.* **2010**, *38*, 453.
[13] R. Neu, M. Balden, V. Bobkov, R. Dux, O. Gruber, A. Herrmann, A. Kallenbach, M. Kaufmann, C. F. Maggi, H. Maier, H. W. Müller, T. Pütterich, R. Pugno, V. Rohde, A. C. C. Sips, J. Stober, W. Suttrop, C. Angioni, C. V. Atanasiu, W. Becker, K. Behler, K. Behringer, A. Bergmann, T. Bertoncelli, R. Bilato, A. Bottino, M. Brambilla, F. Braun, A. Buhler, A. Chankin, et al., *Plasma Phys. Control. Fusion* **2007**, *49*, B59.
[14] L. L. Snead, T. D. Burchell, Y. Katoh, *J. Nucl. Mater.* **2008**, *381*, 55.

[15] J. Roth, E. Tsitrone, A. Loarte, T. Loarer, G. Counsell, R. Neu, V. Philipps, S. Brezinsek, M. Lehnen, P. Coad, C. Grisolia, K. Schmid, K. Krieger, A. Kallenbach, B. Lipschultz, R. Doerner, R. Causey, V. Alimov, W. Shu, O. Ogorodnikova, A. Kirschner, G. Federici, A. Kukushkin, *J. Nucl. Mater.* **2009**, *391*, 1.
[16] V. Philipps, J. Roth, A. Loarte, *Plasma Phys. Controlled Fusion* **2003**, *45*, PII S0741.
[17] V. Philipps, *J. Nucl. Mater.* **2011**, *415*, 2.
[18] J. Roth, E. Tsitrone, T. Loarer, V. Philipps, S. Brezinsek, A. Loarte, G. F. Counsell, R. P. Doerner, K. Schmid, O. V. Ogorodnikova, R. A. Causey, *Plasma Phys. Controlled Fusion* **2008**, *50*, 103001.
[19] R. A. Pitts, S. Carpentier, F. Escourbiac, T. Hirai, V. Komarov, A. S. Kukushkin, S. Lisgo, A. Loarte, M. Merola, R. Mitteau, A. R. Raffray, M. Shimada, P. C. Stangeby, *J. Nucl. Mater.*, *415*, S957.
[20] R. A. Pitts, S. Carpentier, F. Escourbiac, T. Hirai, V. Komarov, S. Lisgo, A. S. Kukushkin, A. Loarte, M. Merola, A. Sashala Naik, R. Mitteau, M. Sugihara, B. Bazylev, P. C. Stangeby, *J. Nucl. Mater.* **2013**, *438*, S48.
[21] R. A. Pitts, X. Bonnin, F. Escourbiac, H. Frerichs, J. P. Gunn, T. Hirai, A. S. Kukushkin, E. Kaveeva, M. A. Miller, D. Moulton, V. Rozhansky, I. Senichenkov, E. Sytova, O. Schmitz, P. C. Stangeby, G. De Temmerman, I. Veselova, S. Wiesen, *Nucl. Mater. Energy* **2019**, *20*, 100696.
[22] G. F. Matthews, P. Edwards, T. Hirai, M. Kear, A. Lioure, P. Lomas, A. Loving, C. Lungu, H. Maier, P. Mertens, D. Neilson, R. Neu, J. Pamela, V. Philipps, G. Piazza, V. Riccardo, M. Rubel, C. Ruset, E. Villedieu, M. Way, ITER-like Wall Project Team, *Phys. Scr.* **2007**, *2007*, 137.
[23] V. Riccardo, M. Firdaouss, E. Joffrin, G. Matthews, P. Mertens, V. Thompson, E. Villedieu, *Phys. Scr.* **2009**, *2009*, 014033.
[24] S. Brezinsek, W. Fundamenski, T. Eich, J. P. Coad, C. Giroud, A. Huber, S. Jachmich, E. Joffrin, K. Krieger, K. McCormick, M. Lehnen, T. Loarer, E. De La Luna, G. Maddison, G. F. Matthews, P. Mertens, I. Nunes, V. Philipps, V. Riccardo, M. Rubel, M. F. Stamp, M. Tsalas, *J. Nucl. Mater.* **2011**, *415*, 936.
[25] Ph. Mertens, J. W. Coenen, T. Eich, A. Huber, S. Jachmich, A. Nicolai, V. Riccardo, K. Senik, *J. Nucl. Mater.* **2011**, *415*, 943.
[26] C. Thomser, V. Bailescu, J. W. Coenen, H. Greuner, T. Hirai, J. Linke, C. P. Lungu, H. Maier, G. Matthews, P. Mertens, R. Neu, V. Philipps, V. Riccardo, M. Rubel, C. Ruset, A. Schmidt, I. Uytdenhouwen, JET EFDA Contributors, in *Int. Conf. on Fusion Reactor Materials, ICFRM-15*, Charleston, SC **2011**.
[27] P. Mertens, J. W. Coenen, S. Devaux, S. Jachmich, I. Balboa, G. F. Matthews, V. Riccardo, B. Sieglin, V. Tanchuk, A. Terra, *Fusion Eng. Des.* **2013**, *88*, 1778.
[28] P. Mertens, V. Philipps, G. Pintsuk, V. Riccardo, U. Samm, V. Thompson, I. Uytdenhouwen, *Phys. Scr.* **2009**, *2009*, 014032.
[29] S. Brezinsek, T. Loarer, V. Philipps, H. G. Esser, S. Gruenhagen, R. Smith, R. Felton, J. Banks, P. Belo, A. Boboc, J. Bucalossi, M. Clever, J. W. Coenen, I. Coffey, S. Devaux, D. Douai, M. Freisinger, D. Frigione, M. Groth, A. Huber, J. Hobirk, S. Jachmich, S. Knipe, K. Krieger, U. Kruezi, S. Marsen, G. F. Matthews, A. G. Meigs, F. Nave, I. Nunes, R. Neu, J. Roth, M. F. Stamp, S. Vartanian, U. Samm, JET EFDA Contributors, *Nucl. Fusion* **2013**, *53*, 083023.
[30] R. L. Neu, S. Brezinsek, M. Beurskens, V. Bobkov, P. de Vries, C. Giroud, E. Joffrin, A. Kallenbach, G. F. Matthews, M.-L. Mayoral, G. Pautasso, T. Putterich, F. Ryter, J. Schweinzer, *IEEE Trans. Plasma Sci.* **2014**, *42*, 552.
[31] R. Neu, G. Arnoux, M. Beurskens, V. Bobkov, S. Brezinsek, J. Bucalossi, G. Calabro, C. Challis, J. W. Coenen, E. de la Luna, P. C. de Vries, R. Dux, L. Frassinetti, C. Giroud, M. Groth, J. Hobirk, E. Joffrin, P. Lang, M. Lehnen, E. Lerche, T. Loarer, P. Lomas, G. Maddison, C. Maggi, G. Matthews, S. Marsen, M.-L. Mayoral, A. Meigs, P. Mertens, I. Nunes, et al., *Phys. Plasmas* **2013**, *20*, 056111.
[32] S. Brezinsek, S. Jachmich, M. F. Stamp, A. G. Meigs, J. W. Coenen, K. Krieger, C. Giroud, M. Groth, V. Philipps, S. Gruenhagen, R. Smith, G. J. Rooij van, D. Ivanova, G. F. Matthews, *J. Nucl. Mater.* **2013**, *438*, S303.
[33] J. W. Coenen, M. Sertoli, S. Brezinsek, I. Coffey, R. Dux, C. Giroud, M. Groth, A. Huber, D. Ivanova, K. Krieger, K. Lawson, S. Marsen, A. Meigs, R. Neu, T. Puetterich, G. J. van Rooij, M. F. Stamp, JET-EFDA Contributors, *Nucl. Fusion* **2013**, *53*, 073043.
[34] G. J. van Rooij, J. W. Coenen, L. Aho-Mantila, S. Brezinsek, M. Clever, R. Dux, M. Groth, K. Krieger, S. Marsen, G. F. Matthews, A. Meigs, R. Neu, S. Potzel, T. Puetterich, J. Rapp, M. F. Stamp, *J. Nucl. Mater.* **2013**, *438*, S42.
[35] G. Arnoux, I. Balboa, M. Clever, S. Devaux, P. De Vries, T. Eich, M. Firdaouss, S. Jachmich, M. Lehnen, P. J. Lomas, G. F. Matthews, P. Mertens, I. Nunes, V. Riccardo, C. Ruset, B. Sieglin, D. F. Valcrcel, J. Wilson, K.-D. Zastrow, JET-EFDA Contributors, *Phys. Scr.* **2014**, *2014*, 014009.
[36] J. W. Coenen, G. F. Matthews, K. Krieger, D. Iglesias, P. Bunting, Y. Corre, S. Silburn, I. Balboa, B. Bazylev, N. Conway, I. Coffey, R. Dejarnac, E. Gauthier, J. Gaspar, S. Jachmich, I. Jepu, C. Makepeace, R. Scannell, M. Stamp, P. Petersson, R. A. Pitts, S. Wiesen, A. Widdowson, K. Heinola, A. Baron-Wiechec, *Phys. Scr.* **2017**, *T170*, 014013.
[37] K. Krieger, B. Sieglin, M. Balden, J. W. Coenen, B. Göths, F. Laggner, P. de Marne, G. F. Matthews, D. Nille, V. Rohde, R. Dejarnac, M. Faitsch, L. Giannone, A. Herrmann, J. Horacek, M. Komm, R. A. Pitts, S. Ratynskaia, E. Thoren, P. Tolias, *Phys. Scr.* **2017**, *T170*, 014030.
[38] G. F. Matthews, B. Bazylev, A. Baron-Wiechec, J. Coenen, K. Heinola, V. Kiptily, H. Maier, C. Reux, V. Riccardo, F. Rimini, G. Sergienko, V. Thompson, A. Widdowson, J. E. T. Contributors, *Phys. Scr.* **2016**, *T167*, 014070.
[39] J. W. Coenen, G. Arnoux, B. Bazylev, G. F. Matthews, A. Autricque, I. Balboa, M. Clever, R. Dejarnac, I. Coffey, Y. Corre, S. Devaux, L. Frassinetti, E. Gauthier, J. Horacek, S. Jachmich, M. Komm, M. Knaup, K. Krieger, S. Marsen, A. Meigs, P. Mertens, R. A. Pitts, T. Puetterich, M. Rack, M. Stamp, G. Sergienko, P. Tamain, V. Thompson, JET-EFDA Contributors, *Nucl. Fusion* **2015**, *55*, 023010.
[40] J. W. Coenen G. Arnoux, B. Bazylev, G. F. Matthews, S. Jachmich, I. Balboa, M. Clever, R. Dejarnac, I. Coffey, Y. Corre, S. Devaux, L. Frassinetti, E. Gauthier, J. Horacek, M. Knaup, K. Krieger, S. Marsen, A. Meigs, P. Mertens, R. A. Pitts, T. Puetterich, M. Rack, M. Stamp, G. Sergienko, P. Tamain, V. Thompson, JET EFDA Contributors, *J. Nucl. Mater.* **2014**, *463*, 78.
[41] G. Sergienko, G. Arnoux, S. Devaux, G. F. Matthews, I. Nunes, V. Riccardo, A. Sirinelli, A. Huber, S. Brezinsek, J. W. Coenen, P. Mertens, V. Philipps, U. Samm, JET EFDA Contributors, *Phys. Scr.* **2014**, *2014*, 014041.
[42] M. Rieth, S. L. Dudarev, S. M. Gonzalez De Vicente, J. Aktaa, T. Ahlgren, S. Antusch, D. E. J. Armstrong, M. Balden, N. Baluc, M.-F. Barthe, W. W. Basuki, M. Battabyal, C. S. Becquart, D. Blagoeva, H. Boldyryeva, J. Brinkmann, M. Celino, L. Ciupinski, J. B. Correia, A. De Backer, C. Domain, E. Gaganidze, C. Garcia-Rosales, J. Gibson, M. R. Gilbert, S. Giusepponi, B. Gludovatz, H. Greuner, K. Heinola, T. Hoeschen, et al., *J. Nucl. Mater.* **2013**, *442*, 173.
[43] J. Reiser, M. Rieth, *Fusion Eng. Des.* **2012**, *87*, 718.
[44] Y. Ueda, K. Schmid, M. Balden, W. Coenen, J. T. Loewenhoff, A. Ito, A. Hasegawa, C. Hardie, M. Porton, M. Gilbert, *Nucl. Fusion* **2017**, *57*, 092006.
[45] C. Bachmann, G. Aiello, R. Albanese, R. Ambrosino, F. Arbeiter, J. Aubert, L. Boccaccini, D. Carloni, G. Federici, U. Fischer, M. Kovari, A. Li Puma, A. Loving, I. Maione, M. Mattei, G. Mazzone, B. Meszaros, I. Palermo, P. Pereslavtsev, V. Riccardo,

P. Sardain, N. Taylor, S. Villari, Z. Vizvary, A. Vaccaro, E. Visca, R. Wenninger, *Fusion Eng. Des.* **2015**, *98–99*, 1423.
[46] J. H. You, E. Visca, T. Barrett, B. Böswirth, F. Crescenzi, F. Domptail, M. Fursdon, F. Gallay, B.-E. Ghidersa, H. Greuner, M. Li, A. V. Müller, J. Reiser, M. Richou, S. Roccella, C. Vorpahl, *Nucl. Mater. Energy* **2018**, *16*, 1.
[47] J. H. You, E. Visca, C. Bachmann, T. Barrett, F. Crescenzi, M. Fursdon, H. Greuner, D. Guilhem, P. Languille, M. Li, S. McIntosh, A. V. Mueller, J. Reiser, M. Richou, M. Rieth, *Nucl. Mater. Energy* **2016**, *9*, 171.
[48] G. Federici, G. Giruzzi, C. Lowry, R. Kemp, D. Ward, R. Wenninger, H. Zohm, in *2013 IEEE 25th Symp. on Fusion Engineering (SOFE)*, IEEE, Piscataway, NJ **2013**, pp. 1–8.
[49] N. Asakura, K. Hoshino, H. Utoh, Y. Someya, S. Suzuki, C. Bachmann, H. Reimerdes, R. Wenninger, H. Kudo, S. Tokunaga, Y. Homma, Y. Sakamoto, R. Hiwatari, K. Tobita, J.-H. You, G. Federici, K. Ezato, Y. Seki, Y. Ueda, N. Ohno, *Fusion Eng. Des.* **2018**, *136*, 1214.
[50] K. Tobita, N. Asakura, R. Hiwatari, Y. Someya, H. Utoh, K. Katayama, A. Nishimura, Y. Sakamoto, Y. Homma, H. Kudo, Y. Miyoshi, M. Nakamura, S. Tokunaga, A. Aoki, *Fusion Sci. Technol.* **2017**, *72*, 537.
[51] K. Okano, R. Kasada, Y. Ikebe, Y. Ishii, K. Oba, M. Kashiwagi, R. Sakamoto, N. Sawa, H. Takenaga, A. Nishimura, M. Fukuie, S. Fujioka, Y. Ueda, T. Akiyama, *Fusion Eng. Des.* **2018**, *136*, 183.
[52] J. Li, G. Luo, R. Ding, D. Yao, J. Chen, L. Cao, J. Hu, Q. Li, *Phys. Scr.* **2014**, *T159*, 014001.
[53] T. Tanno, A. Hasegawa, J. C. He, M. Fujiwara, M. Satou, S. Nogami, K. Abe, T. Shishido, *J. Nucl. Mater.* **2009**, *386–388*, 218.
[54] M. Fujitsuka, B. Tsuchiya, I. Mutoh, T. Tanabe, T. Shikama, *J. Nucl. Mater.* **2000**, *283–287*, 1148.
[55] I. Uytdenhouwen, T. Schwarz-Selinger, J. W. Coenen, M. Wirtz, *Phys. Scr.* **2016**, *2016*, 014007.
[56] J.-H. You, *Fusion Eng. Des.* **2014**, *89*, 294.
[57] J. H. You, G. Mazzone, E. Visca, C. Bachmann, E. Autissier, T. Barrett, V. Cocilovo, F. Crescenzi, P. K. Domalapally, D. Dongiovanni, S. Entler, G. Federici, P. Frosi, M. Fursdon, H. Greuner, D. Hancock, D. Marzullo, S. McIntosh, A. V. Mueller, M. T. Porfiri, G. Ramogida, J. Reiser, M. Richou, M. Rieth, A. Rydzy, R. Villari, V. Widak, *Fusion Eng. Des.* **2016**, *109–111*, 1598.
[58] J. H. You, E. Visca, C. Bachmann, T. Barrett, F. Crescenzi, M. Fursdon, H. Greuner, D. Guilhem, P. Languille, M. Li, S. McIntosh, A. V. Mueller, J. Reiser, M. Richou, M. Rieth, *Nucl. Mater. Energy* **2016**, *9*, 171.
[59] M. Gorley, E. Diegele, S. Dudarev, G. Pintsuk, *Fusion Eng. Des.* **2018**, *136*, 298.
[60] S. J. Zinkle, *Phys. Scr.* **2016**, *2016*, 014004.
[61] A. van Muller, D. Ewert, A. Galatanu, M. Milwich, R. Neu, J. Y. Pastor, U. Siefken, E. Tejado, J. H. You, *Fusion Eng. Des.* **2017**, *124*, 455.
[62] C. H. Henager, W. Setyawan, T. J. Roosendaal, N. R. Overman, B. A. Borlaug, E. L. Stevens, K. B. Wagner, R. J. Kurtz, G. R. Odette, B. N. Nguyen, K. Cunningham, *Int. J. Powder Metall.* **2017**, *53*, 53.
[63] B. N. Nguyen, C. H. Henager, N. R. Overman, R. J. Kurtz, *J. Nucl. Mater.* **2018**, *508*, 371.
[64] R. Neu, H. Maier, M. Balden, R. Dux, S. Elgeti, H. Gietl, H. Greuner, A. Herrmann, T. Höschen, M. Li, V. Rohde, D. Ruprecht, B. Sieglin, I. Zammuto, *J. Nucl. Mater.* **2018**, *511*, 567.
[65] R. E. Nygren, R. R. Dehoff, D. L. Youchison, Y. Katoh, Y. M. Wang, C. M. Spadaccini, C. H. Henager, P. R. Schunk, D. M. Keicher, R. A. Roach, M. F. Smith, D. A. Buchenauer, *Fusion Eng. Des.* **2018**, *136*, 1007.
[66] A. van Müller, G. Schlick, R. Neu, C. Anstätt, T. Klimkait, J. Lee, B. Pascher, M. Schmitt, C. Seidel, *Nucl. Mater. Energy* **2019**, *19*, 184.
[67] D. Maisonnier, D. Campbell, I. Cook, L. Di Pace, L. Giancarli, J. Hayward, A. Li Puma, M. Medrano, P. Norajitra, M. Roccella, P. Sardain, M. Q. Tran, D. Ward, *Nucl. Fusion* **2007**, *47*, 1524.
[68] D. Maisonnier, I. Cook, S. Pierre, B. Lorenzo, D. P. Luigi, G. Luciano, N. Prachai, P. Aldo, *Fusion Eng. Des.* **2006**, *81*, 1123.
[69] T. Wegener, A. Litnovsky, J. Brinkmann, F. Koch, C. Linsmeier, *Nucl. Mater. Energy* **2016**, *9*, 394.
[70] M. Schwarz, G. Hache, P. von der Hardt, *Nucl. Eng. Des.* **1999**, *187*, 47.
[71] T. Kinos, S. L. Chen, P. Siitonen, P. Kettunen, *J. Thermal Spray Technol.* **1996**, *5*, 439.
[72] F. Koch, H. Bolt, *Phys. Scr. T* **2007**, *T128*, 100.
[73] F. Koch, J. Brinkmann, S. Lindig, T. P. Mishra, C. Linsmeier, *Phys. Scr.* **2011**, *2011*, 014019.
[74] P. Lopez-Ruiz, F. Koch, N. Ordas, S. Lindig, C. Garcia-Rosales, *Fusion Eng. Des.* **2011**, *86*, 1719.
[75] E. Joffrin, *J. Nucl. Mater.* **2017**, *486*, 34.
[76] C. Garca-Rosales, P. López-Ruiz, S. Alvarez-Martn, A. Calvo, N. Ordás, F. Koch, J. Brinkmann, *Fusion Eng. Des.* **2014**, *89*, 1611.
[77] P. Lopez-Ruiz, N. Ordas, S. Lindig, F. Koch, I. Iturriza, C. Garcia-Rosales, *Phys. Scr.* **2011**, *T145*, 014018.
[78] M. T. Lessmann, A. Calvo, C. D. Hardie, M. Porton, N. Ordás, C. Garcí-a-Rosales, P. M. Mummery, *Philos. Mag.* **2016**, *96*, 3570.
[79] P. Lopez-Ruiz, N. Ordas, I. Iturriza, M. Walter, E. Gaganidze, S. Lindig, F. Koch, C. Garcia-Rosales, *J. Nucl. Mater.* **2013**, *442*, S219.
[80] P. Lopez-Ruiz, N. Ordas, I. Iturriza, F. Koch, S. Lindig, M. Walter, C. Garcia-Rosales, *Self-Passivating Tungsten Based Alloys Obtained by Hip for Application in Fusion Reactors Beyond Iter (Demo)*, Vol. *4*, Hot Isostatic Pressing, Basel **2012**.
[81] W. Eckstein, J. Bohdansky, J. Roth, *Atomic and Plasma-Material Interaction Data for Fusion*, IAEA, Vienna **2001**.
[82] W. Eckstein, C. Garcia-Rosales, J. Roth, W. Ottenberger. *Sputtering Data, Report IPP 9/82*, Max-Planck-Instut fuer Plasmaphysik, Garching bei München **1993**.
[83] A. Litnovsky, T. Wegener, F. Klein, C. Linsmeier, M. Rasinski, A. Kreter, X. Tan, J. Schmitz, J. W. Coenen, Y. Mao, J. Gonzalez-Julian, M. Bram, *Phys. Scr.* **2017**, *T170*, 014012.
[84] S. Telu, R. Mitra, S. K. Pabi, *Metall. Mater. Trans. A* **2015**, *46*, 1.
[85] F. Klein, T. Wegener, A. Litnovsky, M. Rasinski, X. Tan, J. Schmitz, C. Linsmeier, J. Coenen, H. Du, J. Mayer, U. Breuer, *Metals* **2018**, *8*, 488.
[86] F. Klein, A. Litnovsky, T. Wegener, X. Tan, J. Gonzalez-Julian, M. Rasinski, J. Schmitz, C. Linsmeier, M. Bram, J. W. Coenen, *Fusion Eng. Des.* **2019**, *146*, 1198.
[87] A. Litnovsky, T. Wegener, F. Klein, C. Linsmeier, M. Rasinski, A. Kreter, B. Unterberg, J. W. Coenen, H. Du, J. Mayer, C. Garcia-Rosales, A. Calvo, N. Ordas, *Nucl. Fusion* **2017**, *57*, 066020.
[88] A. Litnovsky, T. Wegener, F. Klein, C. Linsmeier, M. Rasinski, A. Kreter, X. Tan, J. Schmitz, Y. Mao, J. W. Coenen, M. Bram, J. Gonzalez-Julian, *Plasma Phys. Controlled Fusion* **2017**, *59*, 064003.
[89] T. Wegener, F. Klein, A. Litnovsky, M. Rasinski, J. Brinkmann, F. Koch, C. Linsmeier, *Fusion Eng. Des.* **2017**, *124*, 183.
[90] A. Litnovsky, T. Wegener, F. Klein, C. Linsmeier, M. Rasinski, A. Kreter, X. Tan, J. Schmitz, Y. Mao, J. W. Coenen, M. Bram, J. Gonzalez-Julian, *Plasma Phys. Controlled Fusion* **2017**, *59*, 064003.
[91] A. Litnovsky, T. Wegener, F. Klein, C. Linsmeier, M. Rasinski, A. Kreter, B. Unterberg, J. W. Coenen, H. Du, J. Mayer, C. Garcia-Rosales, A. Calvo, N. Ordas, *Nucl. Fusion* **2017**, *57*, 066020.
[92] A. Litnovsky, F. Klein, J. Schmitz, T. Wegener, C. Linsmeier, M. R. Gilbert, M. Rasinski, A. Kreter, X. Tan, Y. Mao, J. W. Coenen, M. Bram, J. Gonzalez-Julian, *Fusion Eng. Des.* **2018**, *136*, 878.
[93] A. Litnovsky, F. Klein, J. Schmitz, T. Wegener, C. Linsmeier, M. R. Gilbert, M. Rasinski, A. Kreter, X. Tan, Y. Mao, J. W. Coenen, M. Bram, J. Gonzalez-Julian, *Fusion Eng. Des.* **2018**, *136*, 878.

[94] J. Schmitz, A. Litnovsky, F. Klein, T. Wegener, X. Y. Tan, M. Rasinski, A. Mutzke, P. Hansen, A. Kreter, A. Pospieszczyk, S. Möller, J. W. Coenen, C. Linsmeier, U. Breuer, J. Gonzalez-Julian, M. Bram, *Nucl. Mater. Energy* **2018**, *15*, 220.
[95] J. Schmitz, A. M. Litnovsky, F. Klein, X. Tan, U. Breuer, M. Rasinski, S. Ertmer, A. Kreter, J. Gonzalez-Julian, M. Bram, J. W. Coenen, C. Linsmeier, *Tungsten* **2019**, *1*, 159.
[96] J. Schmitz, A. Litnovsky, F. Klein, K. D. Lannoye, A. Kreter, M. Rasinski, U. Breuer, J. Gonzalez-Julian, M. Bram, J. W. Coenen, C. Linsmeier, *Phys. Scr.* **2020**, *T171*, 014002.
[97] W. Möller, W. Eckstein, J. P. Biersack, *Comput. Phys. Commun.* **1988**, *51*, 355.
[98] H. Hofsäss, K. Zhang, A. Mutzke, *Appl. Surf. Sci.* **2014**, *310*, 134.
[99] E. Sal, C. Garcí-Rosales, I. Iturriza, I. Andueza, N. Burgos, *Fusion Eng. Des.* **2019**, *146*, 1596.
[100] A. Calvo, C. Garcí-Rosales, N. Ordás, I. Iturriza, K. Schlueter, F. Koch, G. Pintsuk, E. Tejado, J. Y. Pastor, *Fusion Eng. Des.* **2017**, *124*, 1118.
[101] X. Y. Tan, F. Klein, A. Litnovsky, T. Wegener, J. Schmitz, C. Linsmeier, J. W. Coenen, U. Breuer, M. Rasinski, P. Li, L. M. Luo, Y. C. Wu, *Corr. Sci.* **2018**, *147*, 201.
[102] X. Tan, *Powder Technol.* **2020**.
[103] D.-G. Liu, L. Zheng, L.-M. Luo, X. Zan, J.-P. Song, Q. Xu, X.-Y. Zhu, Y.-C. Wu, *J. Alloys Compd.* **2018**, *765*, 299.
[104] J. W. Coenen, Y. Mao, J. Almanstötter, A. Calvo, S. Sistla, H. Gietl, B. Jasper, J. Riesch, M. Rieth, G. Pintsuk, F. Klein, A. Litnovsky, A. V. Mueller, T. Wegener, J.-H. You, C. Broeckmann, C. Garcia-Rosales, R. Neu, C. Linsmeier, *Fusion Eng. Des.* **2017**, *124*, 964.
[105] J. Riesch, J.-Y. Buffiere, T. Hoeschen, M. di Michiel, M. Scheel, C. Linsmeier, J.-H. You, *Acta Mater.* **2013**, *61*, 7060.
[106] J. Riesch, T. Hoeschen, C. Linsmeier, S. Wurster, J.-H. You, *Phys. Scr.* **2014**, *2014*, 014031.
[107] D. M. Hulbert, A. Anders, D. V. Dudina, J. Andersson, D. Jiang, C. Unuvar, U. Anselmi-Tamburini, E. J. Lavernia, A. K. Mukherjee, *J. Appl. Phys.* **2008**, *104*, 033305.
[108] Y. Mao, J. W. Coenen, J. Riesch, S. Sistla, C. Chen, Y. Wu, L. Raumann, R. Neu, C. Linsmeier, C. Broeckmann, *Spark Plasma Sintering Produced W-Fiber-Reinforced Tungsten Composites*, Springer International Publishing, Berlin **2019**.
[109] B. Jasper, J. W. Coenen, J. Riesch, T. Höschen, M. Bram, C. Linsmeier, , *Mater. Sci. Forum* **2015**, *825*, 125.
[110] B. Jasper, S. Schoenen, J. Du, T. Hoeschen, F. Koch, C. Linsmeier, R. Neu, J. Riesch, A. Terra, J. Coenen, *Nucl. Mater. Energy* **2016**, *9*, 416.
[111] Y. Mao, J. W. Coenen, J. Riesch, S. Sistla, J. Almanstötter, B. Jasper, A. Terra, T. Höschen, H. Gietl, M. Bram, J. Gonzalez-Julian, C. Linsmeier, C. Broeckmann, *Phys. Scr.* **2017**, *T170*, 014005.
[112] J. Riesch, M. Aumann, J. W. Coenen, H. Gietl, G. Holzner, T. Hoeschen, P. Huber, M. Li, C. Linsmeier, R. Neu, *Nucl. Mater. Energy* **2016**, *9*, 75.
[113] J. Riesch, Y. Han, J. Almanstötter, J. W. Coenen, T. Höschen, B. Jasper, P. Zhao, C. Linsmeier, R. Neu, *Phys. Scr.* **2016**, *T167*, 014006.
[114] H. Gietl, J. Riesch, J. W. Coenen, T. Höschen, C. Linsmeier, R. Neu, *Fusion Eng. Des.* **2017**, *124*, 396.
[115] J. W. Coenen, Y. Mao, S. Sistla, J. Riesch, T. Hoeschen, C. Broeckmann, R. Neu, C. Linsmeier, *Nucl. Mater. Energy* **2018**, *15*, 214.
[116] Y. Mao, J. W. Coenen, J. Riesch, S. Sistla, J. Almanstötter, A. Terra, C. Chen, Y. Wu, L. Raumann, T. Höschen, H. Gietl, R. Neu, C. Broeckmann, C. Linsmeier **2020**, https://doi.org/10.1002/adem.201901242.
[117] Y. Mao, J. W. Coenen, J. Riesch, S. Sistla, J. Almanstötter, J. Reiser, A. Terra, C. Chen, Y. Wu, L. Raumann, T. Höschen, H. Gietl, R. Neu, C. Linsmeier, C. Broeckmann, *Nucl. Fusion* **2019**, *59*, 086034.
[118] Y. Mao, J. W. Coenen, J. Riesch, S. Sistla, J. Almanstötter, A. Terra, C. Chen, Y. Wu, L. Raumann, T. Höschen, H. Gietl, R. Neu, C. Broeckmann, C. Linsmeier, *Adv. Eng. Mater.* **2020**.
[119] Y. Mao, J. W. Coenen, S. Sistla, X. Tan, J. Riesch, L. Raumann, D. Schwalenberg, T. Höschen, C. Chen, Y. Wu, C. Broeckmann, C. Linsmeier, *Phys. Scr.* **2020**, *T171*, 014030
[120] D. Terentyev, J. Riesch, S. Lebediev, T. Khvan, A. Zinovev, M. Rasiski, A. Dubinko, J. W. Coenen, *Int. J. Refract. Met. Hard Mater.* **2018**, *73*, 38.
[121] D. Terentyev, J. Riesch, S. Lebediev, T. Khvan, A. Dubinko, A. Bakaeva, *Int. J. Refract. Met. Hard Mater.* **2018**, *76*, 226.
[122] D. Terentyev, J. Riesch, S. Lebediev, A. Bakaeva, J. W. Coenen, *Int. J. Refract. Met. Hard Mater.* **2017**.
[123] P. Zhao, J. Riesch, T. Hoeschen, J. Almanstoetter, M. Balden, J. W. Coenen, W. Himml, W. Pantleon, U. Toussaint, R. Neu, *Int. J. Refract. Met. Hard Mater.* **2017**, *68*, 29.
[124] J. Riesch, A. Feichtmayer, M. Fuhr, J. Almanstötter, J. W. Coenen, H. Gietl, T. Höschen, C. Linsmeier, R. Neu, *Phys. Scr.* **2017**, *T170*, 014032.
[125] J. Riesch, J. Almanstoetter, J. W. Coenen, M. Fuhr, H. Gietl, Y. Han, T. Hoeschen, C. Linsmeier, N. Travitzky, P. Zhao, R. Neu, *IOP Conf. Ser.: Mater. Sci. Eng.* **2016**, *139*, 012043.
[126] H. Bolt, V. Barabash, G. Federici, J. Linke, A. Loarte, J. Roth, K. Sato, *J. Nucl. Mater.* **2002**, *307*, 43.
[127] X. Hu, T. Koyanagi, M. Fukuda, N. A. P. Kiran Kumar, L. L. Snead, B. D. Wirth, Y. Katoh, *J. Nucl. Mater.* **2016**, *480*, 235.
[128] V. Müller, G. Schlick, R. Neu, C. Anstätt, T. Klimkait, J. Lee, B. Pascher, M. Schmitt, C. Seidel, *Nucl. Mater. Energy* **2019**, *19*, 184.
[129] Y. Mao, C. Chen, J. W. Coenen, J. Riesch, S. Sistla, J. Almanstötter, A. Terra, Y. Wu, L. Raumann, T. Höschen, H. Gietl, R. Neu, C. Linsmeier, C. Broeckmann, *Fusion Eng. Des.* **2019**, *145*, 18.
[130] S. Schönen, B. Jasper, J. W. Coenen, J. Du, T. Höschen, J. Riesch, G. Natour, R. Neu, C. Linsmeier, *Compos. Interfaces* **2019**, *26*, 1.
[131] H Gietl, A. van Müller, J. W. Coenen, M. Decius, D. Ewert, T. Höschen, P. Huber, M. Milwich, J. Riesch, R. Neu, *J. Compos. Mater.* **2018**, *52*, 002199831877114.
[132] H. Gietl, J. Riesch, J. W. Coenen, T. Höschen, R. Neu, *Fusion Eng. Des.* **2019**, *146*, 1426.
[133] C. S. Bonifacio, T. B. Holland, K. van Benthem, *Scr. Mater.* **2013**, *69*, 769.
[134] C. S. Bonifacio, T. B. Holland, K. van Benthem, *Acta Mater.* **2014**, *63*, 140.
[135] J. R. Groza, A. Zavaliangos, *Mater. Sci. Eng. A* **2000**, *287*, 171.
[136] Y. Mao, J. W. Coenen, J. Riesch, S. Sistla, J. Almanstötter, B. Jasper, A. Terra, T. Höschen, H. Gietl, C. Linsmeier, C. Broeckmann, *Composites Part A* **2018**, *107*, 342.
[137] H. T. Lee, S. Ando, J. W. Coenen, Y. Mao, J. Riesch, Y. Ueda, *Nucl. Mater. Energy* **2019**, *19*, 262.
[138] H. T. Lee, S Ando, J. W. Coenen, Y. Mao, J. Riesch, H. Gietl, R. Kasada, Y. Hamaji, K. Ibano, Y. Ueda, *Phys. Scr.* **2017**, *T170*, 014024.
[139] J. W. Coenen, Y. Mao, S. Sistla, A.V. Müller, G. Pintsuk, M. Wirtz, J. Riesch, T. Hoeschen, A. Terra, J.-H. You, H. Greuner, A. Kreter, C. Broeckmann, R. Neu, C. Linsmeier, *Fusion Eng. Des.* **2019**, *146*, 1431.
[140] L. Raumann, J. W. Coenen, J. Riesch, Y. Mao, H. Gietl, T. Höschen, C. Linsmeier, O. Guillon, *Surf. Coat. Technol.* **2020**, *381*, 124745.
[141] J. W. Coenen, M. Berger, M. J. Demkowicz, D. Matveev, A. Manhard, R. Neu, J. Riesch, B. Unterberg, M. Wirtz, C. Linsmeier, *Nucl. Mater. Energy* **2017**, *12*, 307.

[142] J. M. Missiaen, J. J. Raharijaona, A. Antoni, C. Pascal, M. Richou, P. Magaud, *J. Nucl. Mater.* **2011**, *416*, 262.
[143] W. W. Basuki, J. Aktaa, *J. Nucl. Mater.* **2011**, *417*, 524.
[144] N. P. Taylor, R. Pampin, *Fusion Eng. Des.* **2006**, *81*, 1333.
[145] J. Aktaa, W. W. Basuki, T. Weber, P. Norajitra, W. Krauss, J. Konys, *Fusion Eng. Des.* **2014**, *89*, 913.
[146] H. Greuner, H. Bolt, B. Bswirth, S. Lindig, W. Khnlein, T. Huber, K. Sato, S. Suzuki, *Fusion Eng. Des.* **2005**, *75*, 333.
[147] T. Weber, M. Stüber, S. Ulrich, R. Vaßen, W. W. Basuki, J. Lohmiller, W. Sittel, J. Aktaa, *J. Nucl. Mater.* **2013**, *436*, 29.
[148] Z. Zhou, S. Guo, S. Song, W. Yao, C. Ge, *Fusion Eng. Des.* **2011**, *86*, 1625.
[149] W. W. Basuki, J. Aktaa, *J. Nucl. Mater.* **2012**, *429*, 335.
[150] T. Weber, *Entwicklung und Optimierung von gradierten Wolfram/EUROFER97-Verbindungen für Divertorkomponenten*. Karlsruher Institut für Technologie, Karlsruhe **2014**.
[151] S. Heuer, T. Weber, G. Pintsuk, J. W. Coenen, J. Matejicek, C. Linsmeier, *Fusion Eng. Des.* **2018**, *135*, 141.
[152] S. Van den Kerkhof, M. Blommaert, J. W. Coenen, S. Heuer, M. Baelmans, *Phys. Scr.* **2020**, *T171*, 014001.
[153] S. Heuer, J. W. Coenen, G. Pintsuk, J. Matjek, M. Vilémová, C. Linsmeier, *Phys. Scr.* **2020**, *T171*, 014028.
[154] S. Heuer, T. Lienig, A. Mohr, T. Weber, G. Pintsuk, J. W. Coenen, F. Gormann, W. Theisen, C. Linsmeier, *Composites Part B* **2019**, *164*, 205.
[155] S. Heuer, J. Matejicek, M. Vilemova, M. Kollerm, K. Illkova, J. Veverka, Th. Weber, G. Pintsuk, J. W. Coenen, C. Linsmeier, *Surf. Coat. Technol.* **2019**, *366*, 170.
[156] P. Schuette, *Doctoral Thesis, Ruhr-Universitaet Bochum, Universitaetsbibliothek* **2013**.
[157] H. Nakamura, S. Sakurai, S. Suzuki, T. Hayashi, M. Enoeda, K. Tobita, *Fusion Eng. Des.* **2006**, *81*, 1339.
[158] F. Franza, L. V. Boccaccini, A. Ciampichetti, M. Zucchetti, *Fusion Eng. Des.* **2013**, *88*, 2444.
[159] D. Demange, L. V. Boccaccini, F. Franza, A. Santucci, S. Tosti, R. Wagner, *Fusion Eng. Des.* **2014**, *89*, 1219.
[160] D. Levchuk, F. Koch, H. Maier, H. Bolt, *Phys. Scr.* **2004**, *2004*, 119.
[161] T. Chikada, A. Suzuki, Z. Yao, D. Levchuk, H. Maier, T. Terai, T. Muroga, *Fusion Eng. Des.* **2009**, *84*, 590.
[162] G. W. Hollenberg, E. P. Simonen, G. Kalinin, A. Terlain, *Fusion Eng. Des.* **1995**, *28*, 190.
[163] R. A. Causey, R. A. Karnesky, C. San Marchi, in *Comprehensive Nuclear Materials* (Ed: R. J. M. Konings), Elsevier, Oxford **2012**, pp. 511–549.
[164] M. R. Gilbert, J.-C. Sublet, R. A. Forrest, *Handbook of Activation, Transmutation, and Radiation Damage Properties of the Elements Simulated Using FISPACT-II & TENDL-2014; Magnetic Fusion Plants*, Rep. CCFE, Culham Centre for Fusion Energy, Abingdon **2015**.
[165] J. Engels, A. Houben, P. Hansen, M. Rasinski, C. Linsmeier, *Int. J. Hydrogen Energy* **2018**, *43*, 22976.
[166] J. Engels, A. Houben, M. Rasinski, C. Linsmeier, *Fusion Eng. Des.* **2016**, *124*, 1140.
[167] A. Houben, J. Engels, M. Rasiski, C. Linsmeier, *Nucl. Mater. Energy* **2019**, *19*, 55.
[168] T. Chikada, H. Fujita, J. Engels, A. Houben, J. Mochizuki, S. Horikoshi, M. Matsunaga, M. Tokitani, Y. Hishinuma, S. Kondo, K. Yabuuchi, T. Schwarz-Selinger, T. Terai, Y. Oya, *J. Nucl. Mater.* **2018**, *511*, 560.
[169] T. Chikada, H. Fujita, M. Matsunaga, S. Horikoshi, J. Mochizuki, C. Hu, F. Koch, M. Tokitani, Y. Hishinuma, K. Yabuuchi, Y. Oya, *Fusion Eng. Des.* **2017**, *124*, 915.
[170] T. Chikada, H. Fujita, M. Tokitani, Y. Hishinuma, T. Terai, Y. Oya, *Fusion Eng. Des.* **2018**, *133*, 121.
[171] T. Chikada, K. Kimura, J. Mochizuki, S. Horikoshi, M. Matsunaga, H. Fujita, K. Okitsu, T. Tanaka, Y. Hishinuma, Y. Sakamoto, Y. Someya, H. Nakamura, *Fusion Eng. Des.* **2018**, *146*, 450.
[172] T. Chikada, M. Matsunaga, S. Horikoshi, J. Mochizuki, H. Fujita, Y. Hishinuma, K. Isobe, T. Hayashi, T. Terai, Y. Oya, *Fusion Eng. Des.* **2018**, *136*, 215.
[173] T. Chikada, S. Naitoh, A. Suzuki, T. Terai, T. Tanaka, T. Muroga, *J. Nucl. Mater.* **2013**, *442*, 533.
[174] T. Chikada, M. Shimada, R. J. Pawelko, T. Terai, T. Muroga, *Fusion Eng. Des.* **2014**, *89*, 1402.
[175] T. Chikada, A. Suzuki, C. Adelhelm, T. Terai, T. Muroga, *Nucl. Fusion* **2011**, *51*, 063023.
[176] T. Chikada, A. Suzuki, T. Kobayashi, H. Maier, T. Terai, T. Muroga, *J. Nucl. Mater.* **2011**, *417*, 1241.
[177] T. Chikada, A. Suzuki, T. Kobayashi, Z. Yao, D. Levchuk, H. Maier, T. Terai, T. Muroga, *Fusion Sci. Technol.* **2009**, *56*, 309.
[178] T. Chikada, A. Suzuki, F. Koch, H. Maier, T. Terai, T. Muroga, *J. Nucl. Mater.* **2013**, *442*, S592.
[179] T. Chikada, A. Suzuki, H. Maier, T. Terai, T. Muroga, *Fusion Sci. Technol.* **2011**, *60*, 389.
[180] T. Chikada, A. Suzuki, T. Tanaka, T. Terai, T. Muroga, *Fusion Eng. Des.* **2010**, *85*, 1537.
[181] T. Chikada, A. Suzuki, T. Terai, *Fusion Eng. Des.* **2011**, *86*, 2192.
[182] T. Chikada, A. Suzuki, T. Terai, T. Muroga, F. Koch, *Fusion Eng. Des.* **2013**, *88*, 640.
[183] T. Chikada, A. Suzuki, Z. Yao, D. Levchuk, H. Maier, T. Terai, T. Muroga, *Fusion Eng. Des.* **2009**, *84*, 590.
[184] J. Linke, J. Du, T. Loewenhoff, G. Pintsuk, B. Spilker, I. Steudel, M. Wirtz, *Matter Radiat. Extremes* **2019**, *4*, 056201.
[185] A. Litnovsky, V. S. Voitsenya, R. Reichle, M. Walsh, A. Razdobarin, A. Dmitriev, N. Babinov, L. Marot, L. Moser, R. Yan, M. Rubel, A. Widdowson, S. Moon, S. G. Oh, Y. An, P. Shigin, I. Orlovskiy, K. Y. Vukolov, E. Andreenko, A. Krimmer, V. Kotov, P. Mertens, *Nucl. Fusion* **2019**, *59*, 066029.
[186] C. Linsmeier, B. Unterberg, W. Coenen, J. R. Doerner, H. Greuner, A. Kreter, J. Linke, H. Maier, *Nucl. Fusion* **2017**, *57*, 092012.

