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Plasma-wall Interaction with Reduced-activation Steel Surfaces in Fusion Devices

Summary Report of the Second Research Coordination Meeting

IAEA Headquarters, Vienna, Austria
16–18 October 2017

Prepared by
B. J. Braams and C. Hill

March 2018

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Abstract

Seven experts in the field of plasma-wall interaction on steel surfaces together with IAEA staff met at IAEA Headquarters 16–18 October 2017 for the Second Research Coordination Meeting of an IAEA Coordinated Research Project on Plasma-wall Interaction with Reduced-activation Steel Surfaces in Fusion Devices. They described progress with their research since the previous project meeting in December 2015, discussed open issues and made plans for continued coordinated research during the remaining years of the project. The proceedings of the meeting are summarized in this report.

March 2018

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1. Introduction

The IAEA Coordinated Research Project (CRP) on Plasma-wall Interaction with Reduced-activation Steel Surfaces in Fusion Devices ("Steel Surfaces") is intended to enhance the database on erosion, tritium retention and tritium migration processes in fusion-relevant (reduced activation) steel surfaces. The first Research Coordination Meeting (RCM) of the CRP was held in December 2015 and the summary report is available (report INDC(NDS)-0722, August 2016). This previous summary report and the CRP web site provide more information about the background and the objectives of the project. Please see:

https://www-amdis.iaea.org/CRP/SteelSurfaces/.

As at the first RCM there were seven research groups represented in the second RCM. They are the plasma-wall interaction group at IPP Garching, Germany, the PISCES team at UCSD, USA, the CAS Lanzhou Institute of Chemical Physics, China, the National Institute for Fusion Science (NIFS) in Toki-city, Japan, the Fusion Reactor Department of NRC Kurchatov Institute, Moscow, Russian Federation, the Institute for Plasma Physics in Kharkov, Ukraine, and the Nuclear Research Centre SCK-CEN in Mol, Belgium.

The proceedings of the meeting are summarized in Section 2 and the discussions are summarized in Section 3. Work plan updates are provided in Section 4. The list of participants is in Appendix 1 and the meeting agenda is given in Appendix 2. Summaries of presentations are presented in Appendix 3.

2. Proceedings

Presentation materials for all talks are available through the meeting web page:

https://www-amdis.iaea.org/CRP/SteelSurfaces/RCM2/.

The meeting was opened by A. Koning, Head of the Nuclear Data Section, and participants introduced themselves. This was followed by a review of the CRP goals and meeting objectives by the scientific secretary C. Hill, Head of the Atomic and Molecular Data Unit since October 2017. The broad CRP goal is described as "Increased confidence in assessments of the role of steel as a plasma-facing material in DEMO or a Fusion power plant." It is understood that steel is not suitable as a wall material in the regions of very high heat load, but it may be attractive for other regions of the main wall if erosion and tritium retention properties are under control.

The meeting proceeded with presentations by participants on their group research activities: P. Wang of Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, Lanzhou, China, on Erosion and fuel retention of different RAFM steel grades, W. Jacob of Max Planck Institute for Plasma Physics, Garching, Germany on Developments at IPP regarding sputtering of EUROFER, V. Makhlai of Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology" (NSC KIPT), Kharkiv, Ukraine on Modification and alloying of steel surfaces exposed by powerful plasma streams, R. Doerner of University of California at San Diego, La Jolla, USA onSputtering and D retention properties of RAFM steels under high-flux plasma exposure, D. Terentyev of SCK-CEN Belgium Nuclear Research Centre, Mol, Belgium on Interaction of high flux plasma with Fe and RAFM steels: experimental and computational assessment, Y. Hirooka of National Institute for Fusion Science (NIFS), Toki, Japan on Hydrogen isotopes permeation through the tungsten-coated reduced activation steel first wall of a magnetic fusion reactor, and A. V. Golubeva of NRC "Kurchatov Institute", Moscow, Russia on Hydrogen retention in RAFMs - current status. Summaries of the presentations are provided in Appendix 3.

The presentations and associated discussions were followed by two broad topical discussion sessions. Discussion I: Review of measurements and diagnostic capabilities for erosion and surface composition and plans for coordinated experiments on erosion. Discussion II: Review of measurements and diagnostic capabilities for hydrogen retention and migration and options for coordinated experiments. On the final day participants reviewed their work plans for the remaining period of the CRP and discussed other follow-up actions including plans for the third RCM.

3. Discussion and Conclusions

Following are notes from the discussion sessions. In many cases questions are raised for further study.

Enrichment (of W relative to Fe due to preferential sputtering) is observed and a reduction of erosion is observed that could be due to enrichment. However, the role of changes in surface morphology is not well understood and needs to be considered.

SDTRIMSP calculations suggest that the enrichment cannot explain the reduction in sputtering (hence the interest in morphology as an explanation), but SDTRIMSP as used is not suitable for very thin layers of enriched material. MD simulations are very desirable to clarify the issue, but then these simulations need to cover a long timescale, which is a challenge for MD.

The recent development at CER (UCSD) of real-time spectroscopy can help to clarify the mechanisms and the role of enrichment versus morphology.

In all erosion measurements the role of plasma impurities complicates matters, and the uncertainty in plasma impurity concentration is generally the main source of uncertainty for interpreting the erosion data. In principle, there are two issues: impurities due to background gases, and ionisation of sputtered particles in the plasma and redeposition (which could reduce the net sputter yield) of self-sputtering (which would enhance the yield compared with pure D sputtering). Impurities could also be a problem in non-mass-selected ion beam experiments, but they can be excluded for mass-selection ion beam sources (as for, e.g. the HSQ-I and HSQ-II in IPP Garching). It would be useful (it is recommended) to do more experiments involving controlled variation of impurity content in the plasma.

We recall the very large (factor of 5 or so) discrepancy between erosion due to beam exposure and erosion due to plasma exposure for the case of beryllium surfaces. Fortunately, steel surfaces do not have this issue (in comparative experiments at IPP Garching); presumably because in steel one does not have the dynamic hydrogen concentration effect that is present in beryllium.

The modalities of coordinated experiments on erosion and retention were discussed.

The comparison can involve PISCES at UCSD, SIESTA at IPP Garching, the LEPS device at Lanzhou, the QSPA device at Bochvar (through Kurchatov) and perhaps Magnum-PSI at DIFFER through CKN-CEN.

The sample temperature needs to be standardized; probably something like 500K. One is interested in erosion rates as a function of fluence. A specific energy scan must be agreed; probably energy of about 200eV (for deuterium) is most interesting.

All groups can use plasma Fe spectroscopy as developed at UCSD to obtain erosion data.

It will be interesting to exchange samples again after exposure, but this may not be possible for the PISCES-Be samples.

Dr Doerner stresses that at this time retention is actually a more serious concern than erosion, because the uncertainties in estimated retention rates are so much larger than uncertainties in erosion.

Coordinated gas loading (permeation) experiments were also discussed. Different samples (EUROFER, CLAM, F82H, etc.) could be exposed under agreed conditions and permeability compared. Dr Jacob recommends that this is best done in bilateral or trilateral coordinated experiments. Dr Golubeva volunteers to coordinate gas loading experiments. The samples would be those used anyway in the various labs. A standard size would be something like 10mm * 10mm * 1mm. The pre-annealing and other pre-treatments must be agreed, and probably the samples should be repolished at Kurchatov.

It is agreed that the PSI meeting in June 2018 will provide a suitable venue for a get-together on the topic of coordinated experiments for erosion and retention.

4. Work Plan Updates

Lanzhou Institute of Chemical Physics

The following topics are to be investigated during the remainder of the project.

(1) Erosion of RAFM steel samples extends to higher temperature, to study the surface W enrichment with RBS and TEM.

(2) Compare sputtering yield more precisely using other methods.

(3) Study the fuel retention in steel samples after 3.5 MeV iron ions damaging.

(4) Extend the fuel retention and composition depth profile up to several tens nm region using GDOES.

Retention studies will be done with CLAM steel and CLF-1 steel. New CLF-1 samples are much better characterized than CLAM.

IPP Garching

Continued studies of sputtering by D and He of various steels using the high current ion source SIESTA.

Conclude the work on interdiffusion of Fe, W.

Try to resolve discrepancies between measurements of sputtering (erosion) and SDTRIMSP calculations; decide on the role of enrichment versus the role of morphology.

Arrange sample exchange for coordinated research on erosion (including enrichment) and retention.

NNRC Kurchatov Institute

Two topics are foreseen for year three of the project.

(1) Investigation of influence of radiogenic He on D retention. This involves detritisation of sets of samples every half-year; checking remaining radioactivity; if radioactivity is sufficiently low, expose some samples in D gas and some irradiate with 100 eV D plasma together with samples not containing ^{3}He; finally TDS analysis of retention.

(2) Comparative study of D retention in different RAFMs at high pressures. This involves obtaining samples from other participants and polishing them to remove oxide layer; expose samples of different RAFMs in D at temperature 673 K, pressure in a range of 1 – 20 atmospheres for 24 hours; perform TDS analysis of retention; and compare retention in different RAFMs.

NNRC Kurchatov is also strongly interested in the foreseen coordinated experiments on gas loading.

IPP NSC KIPT Kharkov, Ukraine

The next step of project will be focused on the following issues:

(1) Continuation of studies on modification and alloying of steels under pulsed plasma treatment aimed to increase those sputtering resistance.

(2) Characterization of various steel grades with respect to their response to sputtering by different kind of ions (hydrogen, helium etc.) and dust production under high flux stationary and transient plasma loads.

(3) Comprehensive studies of hydrogen/helium retention (outgassing) in steels modified by pulsed plasma streams in comparison with virgin materials, i.e. without plasma treatment.

Center for Energy Research (CER), University of California at San Diego

The CER group intends to continue their erosion ("S/XB") measurements. The group also intend to study retention under mixed H/He exposure and they have a special interest in F82 steel. Two areas of concentration were mentioned in the main presentation:

(1) D retention properties of RAFM steels: Investigate the fluence and temperature dependence; investigate effect of He mixture; use commercially available P92 FM steel as a surrogate?

(2) In-situ real-time LIBS surface analysis during plasma exposure: Detect surface composition change due to preferential sputtering. (This may not be possible with LIBS.)

SCK-CEN, Belgian Nuclear Research Centre, Mol, Belgium

The group at SCK-CEN will be interested in retention differences between various steels (recrystallized, etc.) and also between Fe-C and steels; Fe-C may be a good reference for RAFM steel. The group also plans to study the effect of plasma exposure on mechanical properties. They intend to cooperate in joint retention experiments. Two specific plans were mentioned in the presentation.

(1) Complete computational model: Assess formation of H clusters at grain boundaries and Carbide-Fe interfaces; assess interaction of H-vacancy-Carbon defects.

(2) Parametric study of the high flux plasma exposure: Exposure temperature: 450K – 850K (upper limit for RAFM); exposure dose: 5×10^{25} – 10^{27} D/m^2; Materials: Fe, Plastically deformed Fe; Eurofer97; "Clean Steel" (no Si & Mn).

NIFS, Toki-city, Japan

Dr Hirooka is planning further bidirectional diffusion experiments for the case of doubly-coated W-steel.

Appendix 1

List of Participants

Peng Wang, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, Lanzhou, CHINA

Wolfgang Jacob, Max Planck Institute for Plasma Physics (IPP), Garching, GERMANY

Yoshihiko Hirooka, National Institute for Fusion Science (NIFS), Toki, JAPAN

Anna Golubeva, Fusion Reactor Department, Division of Tokamak Physics, NRC Kurchatov Institute, Moscow, RUSSIAN FEDERATION

Russel Doerner, University of California at San Diego, La Jolla, California, USA

Vadim Maklai, Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology" (NSC KIPT), Kharkiv, UKRAINE

Dmitry Terentyev, SCK-CEN Belgium Nuclear Research Centre, Mol, BELGIUM

Bastiaan Braams, IAEA Division of Physical and Chemical Sciences, Nuclear Data Section, Vienna International Centre, A-1400 Vienna, AUSTRIA

Christian Hill, IAEA Division of Physical and Chemical Sciences, Nuclear Data Section, Vienna International Centre, A-1400 Vienna, AUSTRIA

Appendix 2

Agenda

Monday, 16 October **Meeting Room: A0407**

09:30 – 09:45 Welcome, adoption of the agenda

09:45 – 10:00 Christian HILL, IAEA: *CRP and meeting objectives*

10:00 – 10:40 Peng WANG, *Erosion and deuterium retention of different RAFM steel grades*

10:40 – 11:00 *Break*

11:00 – 11:40 Wolfgang JACOB, *Developments at IPP regarding sputtering of EUROFER*

11:40 – 12:30 *Discussion*

12:30 – 14:00 *Lunch*

14:00 – 14:40 Vadym MAKHLAI, *Modification and alloying of steel surfaces exposed by powerful plasma streams*

14:40 – 15:20 Russel DOERNER, *Sputtering and D retention properties of RAFM steels under high-flux plasma exposure*

15:20 – 15:40 *Break*

15:40 – 16:20 Dmitry TERENTYEV, *Interaction of high flux plasma with RAFM steels: experimental and computational assessment*

16:20 – 17:00 *Discussion*

19:00 *Social dinner.*

Tuesday, 17 October **Meeting Room: A0407**

09:30 – 10:00 Yoshihiko HIROOKA, *Hydrogen isotopes permeation through the tungsten-coated reduced activation steel first wall of a magnetic fusion reactor*

10:00 – 10:40 Anna GOLUBEVA, *Hydrogen retention in RAFMs –Current status of investigation*

10:40 – 11:00 *Break*

11:00 – 12:00 *Discussion*

12:00 – 14:00 *Lunch*

14:00 – 15:30 *Discussion I: Review of measurements and diagnostic capabilities for erosion and surface composition; plans for coordinated experiments on erosion*

15:30 – 16:00 *Break*

16:00 – 17:30 *Discussion II: Review of measurements and diagnostic capabilities for hydrogen retention and migration; options for coordinated experiments*

Wednesday, 18 October **Meeting Room: A0407**

09:00 – 10:30 *Discussion III: Update of the work plans*

10:30 – 11:00 *Break*

11:00 – 12:30 *Discussion IV: Closing review; sketch of meeting report; plans for next meeting*

12:30 – 14:00 *Lunch*

14:00 Close of meeting.

Presentations

All presentation materials are available on the web page for this meeting:

https://www-amdis.iaea.org/CRP/SteelSurfaces/RCM2/.

Study the interaction of RAFM steel with laboratory and EAST plasma conditions

Peng Wang[1], Li Qiao[1], Liang Gao[2], Wolfgang Jacob[2], Engang Fu[3]

[1]Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, Lanzhou, China

[2]Max Planck Institute of Plasma Physics, Garching, Germany

[3]Peking University, Beijing, China

Dr Wang described recent results obtained on the Linear experiment plasma system (LEPS) in the areas of erosion of CLF-1 steels exposed to deuterium plasma, comparison of sputtering yield of different RAFM steels and of RAFM steels with different roughness and fuel retention in various steel grades.

Developments at IPP regarding sputtering of EUROFER

W. Jacob, K. Sugiyama, M. Balden, M. Oberkofler, T. Schwarz-Selinger, R. Arredondo, M. Reisner, S. Elgeti

Max-Planck-Institute for Plasma Physics (IPP), Boltzmannstr. 2, 85748 Garching, Germany

Dr. Jacob presented an overview of the progress regarding the activities in IPP Garching on issues related to the sputtering of steel. He first presented the new high current ion beam experiment called SIESTA, which has been built and commissioned as a follow-up device for the former "High Current Source (HSQ)". SIESTA has been thoroughly tested and characterised and is fully operational. First control measurements were performed: The angular dependences of the sputtering yields of iron and tungsten due to bombardment with 2 keV deuterium ions were measured. Excellent agreement with SDTrimSP simulation results was found for Fe, while the simulation results for W are higher than the experimental data. While the reason for this deviation is not fully clear, it had been observed also in previous experiments and the current results are in good agreement with those previous experiments.

SDTrimSP is a Monte-Carlo code based on the binary collision approximation that allows the simulation of the sputtering of surfaces due to impact of energetic species. In its dynamic version, it can simulate the dynamic changes of surface composition and sputtering yields upon bombardment of mixed materials. The capabilities of SDTrimSP have been extended to allow tackling the sputtering of Fe-W mixed materials, where very shallow surface enrichment can arise. The new version of SDTrimSP was applied to simulate data that have already been presented in the preceding 1st RCM in 2015 (fluence dependence of the sputter yields of EUROFER due to bombardment with D ions at 100, 200, 500 and 1000 eV). In summary, the agreement between simulation results and experimental data is unsatisfactory. It seems that SDTrimSP cannot reproduce the experimentally found strong decrease of the sputter yield with increasing fluence, which has been observed for sputtering of EUROFER at 200 eV. Also for the other investigated energies, the agreement is quantitatively not very good. Further studies are necessary to achieve a better understanding of the underlying processes.

SDTrimSP was also equipped with a diffusion module to allow studying diffusion effects during sputtering. The experimentally observed increase of the sputter yield of RAFM steels at temperatures above about 700 K is attributed to diffusion of Fe through the W-enriched surface layer thus counteracting the W enrichment due to preferential sputtering. A detailed simulation of these effects is hampered by the fact that the data for interdiffusion of Fe and W are insufficient. To determine diffusion data for the Fe-W system thin W layers were deposited onto pure Fe substrates. The concentration changes at the Fe-W interface due to extended annealing in the temperature range from 900 to 1150 K was studied by ion beam analysis, SEM cross sectioning and EDX analysis. One observation is that in addition to diffusion gradients a stable Fe_2W phase is formed at the interface. The evaluation of the measured concentration profiles is ongoing.

Finally, some contributions of IPP Garching to the European work programme for the development of thermonuclear fusion, which is coordinated within the EURO*fusion* project, were reviewed.

Modification and alloying of steel surfaces exposed by powerful plasma streams

V. Makhlai

Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology" (NSC KIPT), Kharkiv, Ukraine

Tungsten coatings can also be alternative to the monolithic material, especially for large area of the DEMO reactor first wall. Reduced-activation Steels (RAFMs) are one of main material for next step fusion devices. However, the large sputtering rate under high energy particles is main disadvantage of steels as armour plasma-facing material. One of the potential ways of improving these properties is alloying of surface layers of materials with heavy elements. For example, alloying of surface layer by mixing previously deposited thin ($h_{coat} < h_{melt}$) coatings is one of possibility options.

Experimental studies of surface modification of Eurofer and Rusfer samples covered by tungsten coatings have been performed with a quasi-stationary plasma accelerator QSPA Kh-50 and magneto-plasma compressor MPC. The heat load on the surface was near the tungsten melting threshold (i.e. about 0.6 MJ/m^2, pulse of hydrogen plasma with duration of τ= 0.25 ms for QSPA Kh-50 and about 0.4 MJ/m^2, pulse of helium plasma with duration of τ= 20 µs for MPC). Tungsten coatings of 3 µm were preliminary deposited by PVD method in facility of Bulat family. The sputtering tests of modified surfaces were also performed with Argon ion beam with ions energy of 600 eV and current density of 1.6 mA/cm^2.

The possibility of alloying of Eurofer and Rusfer surfaces with tungsten was demonstrated. Tungsten phase is recognized together with lines of Fe phase on treatment surfaces. The concentration of tungsten has been achieved several tens wt% in surface layer up to 4 µm. The surface morphology is developed mostly by melting and re-solidification of a surface layer. Macro and micro cracks appear also on modified surfaces. The delamination of coatings is also observed, especially when the surface is irradiated by short plasma streams. Differences of the sputtering yield of modified samples and yield of samples in initial state are negligibly. That is caused destroyed of modified layer and delamination of coatings due to not good adhesion.

The possible way to improve coatings resistance is application of several cycles of plasma treatment. One cycle consists of two stages: (1) deposition of thin tungsten coating of 1-2 µm; (2) the coated samples should be processed with pulsed plasma. Some decrease of coating thickness together with increasing of number of cycles of plasma treatment creates condition for penetration of alloying element in depth of substrate.

The next step of project will be focuses on next issues relevant to plasma-facing materials of fusion reactor: (1) Continuation of studies on modification and alloying of steels under pulsed plasma treatment aimed to increase those sputtering resistance. (2) Characterization of various steel grades with respect to their response to sputtering by different kind of ions (hydrogen, helium etc.) and dust production under high flux stationary and transient plasma loads. (3) Comprehensive studies of hydrogen/helium retention (outgassing) in steels modified by pulsed plasma streams in comparison with virgin materials, i.e. without plasma treatment.

Sputtering and D retention properties of RAFM steels under high-flux plasma exposure

R. P. Doerner and D. Nishijima

University of California - San Diego, La Jolla, California, USA

The PISCES presentation covered three topics; 1) sputtering from RAFM steel, 2) preliminary results from D retention behavior of RAFM steels and 3) LIBS measurements of surface composition.

In the first section, sputtering properties of F82H and CLF-1 RAFM (reduced activation ferritic/martensitic) steels are investigated under exposure to high-flux He plasmas ($G_i \sim 2\text{-}4\text{x}10^{22}\ \text{m}^{-2}\text{s}^{-1}$) in PISCES-B with a low incident ion energy of ~80 eV and sample temperature, T_s, ranging from ~573 K to 1053 K. Both steels are primarily alloys of Fe, Cr, and W. While sputtered W atoms were not detected during the exposure, sputtered Fe and Cr atomic fluxes were spectroscopically quantified using *S/XB* values of Fe I and Cr I emission lines, which were experimentally determined in this study. Sputtering yields of F82H obtained from spectroscopy agree well with those from mass loss measurements. The He^+ fluence-integrated sputtering yield of F82H and CLF-1 does not depend on T_s in the range of ~ 573-873 K, but starts to increase at T_s ~ 900 K. Sputtered Fe and Cr atomic fluxes are found to drop during the plasma exposure. The reduction of sputtering yield is explained by surface enrichment of W and development of surface morphology. The surface enrichment of W was measured with Auger electron spectroscopy, and is due to the observed preferential sputtering of Fe and Cr. Cone-like structures were observed with a scanning electron microscope, which become larger with increasing T_s, and W fuzz is formed on top of the cones at $T_s \geq 973$ K.

Deuterium retention measurements from PISCES showed agreement with other data for Eurofer and values that were somewhat higher (~ 4 times larger) for CLF-1 steel compared to data from other devices. In addition, there was negligible retention in F82H steel exposed to D plasma, in contradiction to other device data.

Finally, plans and preliminary data using LIBS to measure the composition of thin surface layers were described. A novel technique, spatially-offset double-pulse laser-induced breakdown spectroscopy (SODP-LIBS), was described for analysis of thin layers. In this technique, two laser spots are spatially offset by a few mm, compared to standard double-pulse LIBS where no offset is used. The spatial offset allows the enhancements associated with DP-LIBS measurements by interacting with areas of the surface containing the surface layer during the second laser pulse, whereas in standard DP-LIBS the second layer would encounter a surface region where the layer had been removed by the first laser pulse.

Interaction of high flux plasma with iron and reduced activation ferritic steels: experimental and computational assessment

Dmitry Terentyev

SCK-CEN Belgium Nuclear Research Centre, Mol, Belgium

As a contribution to the CRP on "Plasma–Wall Interaction with Reduced Activation Steel Surfaces in Fusion Devices", over 2016-2017 we have performed both computational assessment and certain experimental work to characterize the impact of high flux deuterium plasma on the iron and several selected RAFM steels. In both cases, the analysis was mainly dedicated to understanding of the trapping and retention of D atoms in the matrix, and microstructural changes induced by the high flux plasma.

An in-depth computational analysis was performed using ab initio methods to characterize the residence of H atoms in bcc Iron matrix and its self-interaction, interaction with vacancies and dislocations. It has been revealed that H exhibits rather weak self-interaction (binding energy of 0.22 eV), and formation of multiple hydrogen clusters is not conducted by the release of self-interstitial Fe thus creating the thermally stable H_n-vacancy complex – contrary to the situation with Helium. The interaction energy with screw and edge dislocation was found to be 0.27 and 0.47 eV, respectively. However, the energy landscape of corresponding to the H_n cluster on the dislocation line neither revealed a possibility of the transformation of such complex into the stable cluster accommodated with the emission of kinks.

Finally, the binding of H and H_n clusters with a single vacancy was assessed. The binding of a single H amounts to 0.62 eV, and two more H atoms are bound without losing the binding strength. Fourth and fifth atoms can be further added, but the corresponding binding energy goes down to 0.2 eV. The addition of the sixth atom is no longer favourable. Hence, at the current stage, it is not clear how the growth of H_n cluster on vacancy or dislocation line can occur without the external source of free vacancies, required for the accommodation of upcoming H atoms (due to influx from the plasma).

On the experimental side, two sets of exposure were performed, namely: (i) pure Iron in reference and heavily deformed state; (ii) exposure of several RAFM steels including two chemically tailored grades produced specially to improve the mechanical properties and two conventional 9Cr steels – Eurofer97 and T91. Two advanced grades were produced by applying thermo-mechanical-chemical (TMC) treatment. By performing primary mechanical testing it has been revealed that while preserving acceptable yield strength and ultimate tensile strength, the ductile to brittle transition temperature was shifted down to approximately -140 °C. This grade and two standard 9Cr grades (T91 and Eurofer97) have been selected for the preliminary high flux plasma exposures at Pilot-PSI linear plasma generator in Netherlands. The exposure temperature was 450K. The thermal desorption spectroscopy (TDS), scanning electron microscopy (SEM) and transmission electron microscopy (TEM) analysis has been performed on as-exposed materials. The TDS has revealed one major release stage at 450K-500K and several minor release stages in the temperature range 700-1000K. Plastic deformation applied to pure Fe resulted in the increase of the trapping of H released at stage I, but also invoke the appearance of the second release stage around 650K. It has been discussed that this release stage is probably due to the pinning at the sub-grains formed as a result of the heavy plastic deformation. The SEM analysis revealed quite strong surface modifications in a form of slip bands, roughening and rarely observed blister-like surface defects (the nature is still to be confirmed) in pure Fe and conventional RaFM steels. The surface modification was clearly less evident for the advanced TMC grade.

For the remaining time of the CRP, it is planned to complete the computational analysis and perform calculations to evaluate a possibility of the nucleation of H clusters on the grain boundaries, also consider the impact of carbon and chromium.

Besides, the new plasma exposures will be performed at Magnum PSI at 450K involving pure Fe and Eurofer 97 to complete the matrix of the experimental results where the effect of flux is of concern. The samples will be analysed by applying TDS, SEM and TEM techniques.

Hydrogen isotopes permeation through the tungsten-coated F82H first wall

Yoshi Hirooka[1,2] and Yue Xu[2]

National Institute for Fusion Science, Toki, Japan

[2]Graduate University for Advanced Studies (currently Hefei Univ. Tech.), Hefei, China

As part of the stellerator DEMO reactor design study R&D at the National Institute for Fusion Science (to be referred to as NIFS) [1], hydrogen isotopes permeation through a reduced activation ferritic steel alloy: F82H as the candidate material for the first wall has been investigated since 2011.

As is often the case with fusion power reactor studies, the thickness of the first wall is designed to be ~5mm, and the operation temperature is intended to be ~500ºC in the case of the DEMO reactor study at NIFS, which would result in "bi-directional" hydrogen isotopes transport processes. These are: (1) plasma-driven permeation (to be referred to as PDP), by which D, T are transported from the edge plasma into the breeding blanket, and (2)

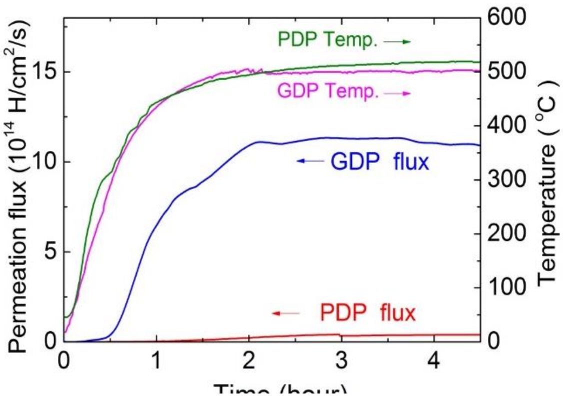

Fig. 1 Hydrogen GDP and PDP at 500ºC through 5mm thick F82H [1].

gas-driven permeation (GDP) by which bred T is transported from the breeding blanket to the edge plasma.

The first phase of investigation: 2011-2014 focused on F82H without protective coatings and the second phase: 2015-2017 has been intended to evaluate the effects of tungsten coatings on hydrogen isotopes permeation. From the first phase, as shown in Fig. 1, it was found out that the GDP-T flux can be just as high as 1 torr liter/cm^2/s, meaning that the total GDP flow of T into the edge plasma can be of the order of 1000 torr liters/s for a DEMO reactor with the total first wall surface area of typically ~1000m^2. In contrast, the PDP hydrogen flux was measured to be orders of magnitude lower than this.

Based on these data, the use of a permeation barrier has been proposed and tungsten has been chosen as the coatings material. In the second phase of investigation, tungsten coatings have been prepared by: (1) vacuum plasma spray (to be referred to as VPS-W), and (2) sputter deposition (to be referred to as SP-W). From the materials characterization analysis, it has been found that VPS-W has relatively low densities ~90% with connected pores whereas SP-W has densities as high as 99.5%.

It has been found that VPS-W coatings can suppress only hydrogen PDP from the plasma side, whereas SP-W can suppress only hydrogen GDP from the blanket side [3]. Therefore, the use of VPS+SP double layer coatings has recently been proposed, and the preliminary data (to be published) indicate that both PDP and GDP can be suppressed by several orders of magnitude.

[1] A. SAGARA et al., Fusion Technol., **39**(2001)753.

[2] Yoshi HIROOKA and H. ZHOU, Fusion Sci. Technol. **66**(2014)63.

Hydrogen retention in RAFMs –Current status of investigation

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In next-step fusion devises (DEMO reactor and hybrid fusion-fission reactor) neutron fluxes and resulting damage of materials will be significantly higher than in ITER. The tritium decay will lead to formation of radiogenic helium in the bulk of plasma-facing and constructive materials. These processes will lead to structure changes of materials and will influence tritium retention.

The aim of the project is to model experimentally damages in fusion facilities and investigate their influence on hydrogen retention in RAFMs. One of the main goals is to investigate influence of radiogenic He formation on deuterium retention afterwards. For radiogenic He creation in materials the “tritium trick” method was selected. In this method samples are exposed in tritium gas, dissolving some amount of tritium. The one should wait for He formation in reaction of T decay:

$_1T^3 \rightarrow {}_2He^3 + e^- + \nu$,

and after necessary time remove T from samples by annealing.

A new installation for samples exposure in tritium was designed and manufactured in A.A. Bochvar’s institute, Russia. Materials under investigation was Rusfer and Eurofer RAFMs, austenitic steel ChS68, W and CuCrZr bronze for comparison. For the first samples were exposed in D_2 gas at a pressure of 20 atmospheres, temperature of 673 K during 24 and 100 hours. The deuterium retention was measured by TDS method.

The result on deuterium retention were repeatable for samples of the same material exposed at the same conditions. Deuterium retention in materials is distributed the following:

Retention in bronze > retention in austenitic steel > retention in RAFMs Rusfer > retention in W.

The “>” sign means the difference about an order of magnitude. It was concluded that exposition during 24 hours is enough for saturation the materials.

The exposition in T gas was performed at a pressure of 8 atmospheres, temperature 673 R during 24 hours. The imaging plate method was used for estimation of T distribution across the surface. The samples were left in inert gas for He^3 production. It is planned to make detritisation of first portion of samples within half a year.

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