Minutes of the Tungsten IEA Workshop

October 12, 2015

Eurogress Conference Center

Aachen, Germany

Chair: C.H. Henager (US)

The Agenda for this meeting is Attachment 1.

1. Introduction

The workshop began with a brief welcome and statement from the chair regarding the purpose of the workshop and announcing the agenda. The purpose was stated as information sharing and a brief discussion of future directions. However, the chair reminded the attendees that most of the two hours allotted for the workshop would be given over to the presentations of activities by the various countries and groups and that the discussion time would be very brief.

The chair noted that 1 plenary, 26 orals, and over 60 posters were devoted to tungsten and tungsten alloys for fusion reactors and that tungsten was apparently the top priority at ICFRM-17. This was supported by the fact that this meeting had over 45 attendees, which was estimated by the fact that the room could hold 40 to 50 and that some attendees had to stand. Unfortunately, no attendance list was circulated, which was an oversight by the chair. However, the chair has an up to date email list of over 70 international researchers that have requested to be part of the IEA mailing list for tungsten.

2. Overview of National Programs and Research Thrusts

Dr. Jan Coenen gave the EUROFusion overview presentation and discussed the operational window of tungsten according to a low temperature threshold of radiation hardening and lack of low-temperature toughness and a high temperature threshold of recrystallization or other high-temperature degradation processes. For tungsten in a fusion neutron spectrum then this temperature operational window changes during operation due to many factors, including helium, rhenium, and osmium transmutation that will degrade the fracture toughness. Recrystallization, microstructural evolution, and conventional radiation hardening will also further degrade tungsten.

The EUROFusion approach is to address these issues using 1) composite technologies, 2) self-healing or damage tolerant materials, 3) smart materials. An integrated approach is preferred for this in terms of studies on integrated components.

Composites include K-doped W-wires with oxide interfaces (Er, Y, Zr) and CVI or powder metallurgy (PM) consolidation methods. Powder injection molding (PIM) is being used to produce large-scale W parts for testing. W-WC composites are being studied at IJS in Slovenia and W-Ti-foil+SiC_f composites by hot-isostatic pressing (HIP).

Smart alloys include new W-Y-Cr alloys of W-12%Cr-0.3%Y, such that these alloys have much greater oxidation resistance compared to pure W in the case of LOCAs. W joined to steels via functionally graded materials is also studied. Tritium management is controlled by permeation barriers on W.

In terms of component manufacturing, one emphasis is on activation analysis and controlling the amount of Cu and Er. The main issues to be addressed by component manufacturing include 1)

Lifetime of PFCs and Joints due to erosion/creep/fatigue/embrittlement, 2) Thermal properties of composites and components - Maximize heat flux to coolant — thin PFCs, 3) Compatibility with tritium breeding, 4) Maximize damage resilience for both external as well as internal damage (e.g. cracks & neutrons), 5) Maintainability - Recycling of used materials / components e.g. minimize activation, and 6) Large scale production of advanced materials / components. These are recognized as large challenges. The aim is a component - HHF/ PWI testable <5 years (TRL 5-6). Test Samples are needed on short timescales to test PWI - & exhaust relevant parameters. How do we integrate our efforts between the component relevant materials? We consider also forbidden materials such as Cu, Al, Er, e.g. Y. We need to understand neutron effects on materials.

Dr. Henri Greuner discussed GLADIS as a unique EU facility for operation with H, He or mixed H/He neutral beams and thermal loads that has been recently upgraded to ITER and DEMO conditions for water cooling with T_{in} of 20˚C to 230˚C ± 1˚C and T_{out} of 250˚C. The successful testing of W/CuCrZr multilayer composites up to 20 MW/cm^2 was discussed with one failure identified due to manufacturing defects. Also, testing of W monoblock on W/Cu laminate tubes at 13 MW/cm^2 was completed. Further work on W-composites and basic science work on erosion and H/He inventory was discussed.

Dmitry Terentyev discussed tungsten research at CEN/SCK as 1) testing after neutron and ion irradiation, 2) High temperature mechanical testing (cold), 3) Microstructural examination, 4) Electron irradiation, 5) Large-scale plastic deformation, 6) Micro-mechanical testing, 7) Positron Annihilation Spectroscopy, and 8) Integrated Modeling.

Jiri Matjicek of IPP Prague discussed that IPP was involved in materials development and testing. Materials for tungsten coatings are developed using plasma spraying for which progress was made by spraying at deposition temperatures over 700˚C to avoid porosity. Functionally graded W-Fe materials are being developed for bonding W to RAFM steels. Spark plasma sintering is being pursued to densify W-TiC and W-Y_2O_3 composites. Material testing is being pursued using ELM simulation by combined D plasma+laser loading of SPS W with varying grain size. The finding was that a fine-grained W roughens but does not crack in contract to a larger-grained W that roughens and cracks. Other activities within the EU include 1) Pulsed plasma loading up to melting, 2) Arcing on He fuzz, 3) Exposure of various W grades to hot He gas, and 4) Laser repair of cracked W.

George Smith of Oxford Univ., UK discussed W-ion irradiations of W-Re, W-Ta, W-Re-Os, and W-Re-Ta alloys and examination using atom probe tomography (APT), which elucidated the strong effects of Os and Ta on Re clustering during irradiation. This work suggests that Os will have a large impact on W-Re alloys or even on pure W that undergoes Re and Os transmutations. High heat flux testing is also being pursued using a simple oxyacetylene torch heating. W/WC (cemented carbide tooling) is being investigated in this manner.

Prof. Liu of Southwest Institute of Physics (SWIP) discussed China's tungsten program in terms of pure tungsten (ITER grade W and CVD-W coating with fast deposition rate), W alloys consisting of ODS-W (W-La_2O_3, W-Y_2O_3) and CDS-W (W-TiC, W-ZrC) and W-K alloys, W composites (Nano fiber enhanced W and Nano lamellar W). Thermal shock testing was significant with up to 3.5 MJ/m^2 exposure testing for surface damage.

Several kinds of advanced W-based materials are being developed, such as ODS-W, CDS-W, nano fiber and nano lamellar enhanced W, but the latter is just beginning. Some W alloys exhibit good thermo-mechanical properties, in particular low temperature ductility. CVD-W coating shows more sensitivity to base temperature since normally the cracks disappear when base temperature is over 200°C, it may be owing to its special columnar structure and high temperature strength. New developed W-ZrC, W-K alloys show higher crack thresholds, nearly close to melting ones, their temperature effects are under investigation. Moreover, besides the evaluation by heat loading, low energy ion irradiation tests are also be carried out, they hope to rank the different W grades.

Yutai Katoh or ORNL discussed the US program in tungsten as more focused on fundamental understanding. Work includes neutron irradiation of single crystal W, W-Re APT studies, thermal desorption studies, W-Cu laminate development, and the newer PHENIX collaboration with Japan (to be discussed by Y. Hatano in this meeting).

Yuji Hatano, Univ. of Toyama, discussed the newer US-Japan collaboration, PHENIX (PFC evaluation by tritium **P**lasma, **HE**at and **N**eutron **I**rradiation e**X**periments), designed to evaluate the feasibility of He gas-cooled divertor with tungsten material armor for DEMO reactors. The use of HFIR reactor at ORNL is being utilized for this work studying W at irradiation temperatures of 500, 800 and 1200 ˚C, irradiation doses to 1–1.5 dpa, thermal neutron shielding (Gd) since thermal neutron shielding is essential for fusion-relevant transmutation, and using specimens for hydrogen isotope retention and permeation measurements consisting of W, W-Re, K-doped W-Re, UFG-W, and layered materials. Irradiation test RB19J is scheduled to be removed form HFIR by July 2017 with PIE lasting until March of 2019. Additional fundamental data is being acquired fusing positron annihilation spectrometry (PAS) in Japan.

Akira Hasegawa discussed the core of the Japanese program in tungsten as 1) Tungsten material development for plasma-facing components, 2) Irradiation effects on fusion reactor materials (i.e. RAFM and W), 3) Analysis of the structural response of fusion reactor components by computer simulation, and 4) Development of the residual life prediction and mechanical property investigation technology for fusion and fission reactor component materials. Development of fatigue test technology, underwater explosive bonding of W to RAFM steels (F82H), and deuterium retention of W exposed to high heat flux plasmas were also discussed.

Hyoung Kim of NFRI, South Korea, discussed "Tungsten PFC Development & Testing - Overview of Tungsten Research in Korea". NFRI is performing R&D on tungsten materials for fusion via tungsten PFC development of tungsten bonding technology, design and optimization of tungsten PFC, study on damage, lifetime of tungsten PFC, material test & surface morphology, heat load analysis on tungsten tiles, fuel retention and its removal, and investigation of plasma-wall Interactions. PFC mockups have been developed and are being tested in KoHLT-EB (Korea Heat Load Test facility-Electron Beam) in KAERI, which scans the whole area of a mockup with electron beam of 10 mm in diameter & 10 kHz in frequency. Further high heat flux testing is being performed in KSTAR, which delivers about 3-5 MW/m^2 ELM-like exposures to PFC materials.

3. Discussion of Potential Collaborations

Following the presentations, little time was available for the large group to discuss potential collaborations. The chair suggested round robin testing and test specimen validation but that was not compelling. One suggestion was that the IEA could play a role in performing simple composite strength calculations to help guide W/W type composite development, particularly in the wake of the severe degradation that is now known to occur. The meeting adjourned without a consensus of possible collaborations due to time constraints.

4. Tungsten Working Group Chair

A new chair for the Tungsten Working Group needs to be selected. A new chair should be identified well in advance of the next meeting of the working group. The names and brief biographical information on candidates should be sent to the ExCo.

5. Place and Date of Next IEA Tungsten Meeting

No meeting date or time was set.

6. Adjourn

The meeting was adjourned at 18:30.

Attachment 1

ICFRM-17 Aachen Tungsten IEA Meeting Agenda
Monday, October 12, 2015 16:30 to 18:30 Konf 4

1.	16:30 – 16:35 (5)	Brief Meeting Introduction	Chuck Henager	PNNL
2.	16:35 – 16:55 (20)	Adv. Material Development EUROFusion (CEIT,IPP,FZJ,KIT,IJS)	Jan Coenen	FZJ
3.	16:55 – 17:05 (10)	GLADIS Experiments	Henri Greuner	MPI/IPP
4.	17:05 – 17:15 (10)	Tungsten R&D CEN/SCK	Dmitry Terentyev	CEN/SCK
5.	17:15 – 17:25 (10)	Tungsten Experiments Overview	Jiri Matejicek	IPP Prague
6.	17:25 – 17:35 (10)	Tungsten Irradiations: W/WC	George Smith	Oxford Univ.
7.	17:35 – 17:45 (10)	Summary of Chinese Program	Xiang Liu	SW Inst. Phys.
8.	17:45 – 17:55 (10)	ORNL Tungsten Summary	Yutai Katoh	ORNL
9.	17:55 – 18:05 (10)	Summary of PHENIX US-Japan	Yuji Hatano	Univ. Toyama
10.	18:05 – 18:15 (10)	W-material Development	Akira Hasegawa	Tohoku Univ.
11.	18:15 – 18:20 (5)	Status of Tungsten PFC Dev. and Testing	Hyoung Kim	NFRI, Korea
12.	18:20 – 18:30 (10)	Discussion of Potential Collaborations (until room is closed)		

a. Possible round robin test specimens for PFC testing.

b. Possible round robin test specimens for mechanical properties.