EFDA WORKPROGRAMME 2010

Call for Participation

Emerging Technologies

Fusion Materials Topical Group

Research Project:
MAT-WWALLOYS: Tungsten and Tungsten Alloys Development

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1. Introduction

At its meeting in Barcelona on the 8th July 2009 the EFDA Steering Committee approved the EFDA 2010 Workprogramme, including the tasks identified below. This Call for Participation covers the activities of the 2010-WP of the MAT-WWALLOYS Research Project of the Fusion Materials Topical Group, Tungsten and Tungsten Alloys Development, and will be implemented on the basis of the provisions given in Art.5 of the EFDA Agreement.

2. Objectives

Tungsten and tungsten alloys are presently considered for helium cooled divertor and possibly for the protection of the helium cooled first wall in DEMO designs, mainly because of their high temperature strength, good thermal conductivity, and low sputtering rates. There are two types of applications for these materials which require quite different properties: one is the use as plasma-facing armour or shield component, the other is for structural purposes. An armour material needs high crack resistance under extreme thermal operation condition and plasma wall interaction, while a structural material has to be ductile within the operation temperature range. Both material types have also to be stable with respect to high neutron irradiation doses and helium production rates.

The Research Project is structured into:

- four lines of classical engineering research:

- Fabrication Process Development
- Structural Material Development
- Armour Materials Optimisation
- Irradiation Performance Testing

- and a basic research line:

- Materials Science and Modelling

The main objectives are the following for each programmatic line.

2.1 Fabrication Process Development:

This includes joining, machining, fabrication process development, and mock-up testing on the basis of the current He cooled divertor design (pure tungsten as armour material for tiles, W-1%La_2O_3 as structural material, commercial brazing materials, operation temperature 600-1300 °C). Within this area, fabrication, operation, and lifetime issues are treated. The present finger design is treated as a preliminary test case.

Long term objectives:

- Providing all the fabrication steps and processing parameters for divertor part assembly.
- Verification of reliability and lifetime of divertor parts with relevant component tests (tests in special helium loop facilities and/or tokamaks).

Objectives for 2010:

Identification of fabrication related material issues and implications for tungsten materials development. In general, Eurofer is going to be used as structural material, with the expectation that ODS steels will replace Eurofer in various parts of the structure in the future.

I. Joining:

After screening studies of commercial brazes or materials with property gradient not complying with Reduced Activation fusion requirements in WP-08-09, the work is re-oriented to the development of Reduced or Low Activation alloys for brazing or advanced joining:

a) Development and testing of ***low activation brazing*** materials for joining tungsten to tungsten (high operation temperature), especially Ti-based brazes.
b) Development and testing of ***reduced activation brazing*** materials for joining tungsten to Eurofer steel (medium operation temperature).
c) Development of functional gradient materials for the transition from W to Eurofer steel, using co-sintering by classical route or via Pulse Plasma sintering or laser deposition of property gradient alloys with Low or Reduced activity.

Feasibility of explosive bonding in the case of tungsten-EUROFER plane joint geometry will also be carried out.

II. Machining:

a) Investigating and characterising fabrication techniques as alternatives to Electrical-Discharge-Machining (EDM). Fabrication of crack-free surfaces, e.g. with electro-chemical machining (ECM).
b) Developing mass production methods for divertor parts (finger and tiles): deep drawing and Powder Injection Moulding (PIM).

2.2 Structural Materials Development

This part is focussed on materials development and basic characterisation. The goal is to find a ductile refractory material with acceptable thermal conductivity. The measurements for comparing ductility are either standard Charpy tests on miniaturized specimens or bending tests with different strain rates which allow for extrapolation to the same dynamic loads compared to Charpy tests.

Long term objectives:

- Industrial scale production of a refractory material for structural divertor applications.
- Oxidation protection (coating)
- Full characterisation (including data base) of such a material.

Objectives for 2010:

The basic screening of 2008-2009 has confirmed the selection of W-Ta (as reference), W-V and W-Ti in severely deformed microstructure after warm or hot process, to be used for low temperature. ODS variants are also studied for improved thermal stability. The goal is to improve/optimise thermal stability of the microstructure and of the ductility and fracture toughness of tungsten materials.

I. Material Production:

a) Production and metallurgical characterisation of W-Ta, W-V and W-Ti tungsten materials by powder mixing, pressing, sintering, and final cold/hot work.
b) Production and metallurgical characterisation of W-V and W-Ti tungsten ODS materials by mechanical alloying (milling) or mixing, hot isostatic pressing, and eventually cold/hot work.

II. Basic Characterisation

For clear comparison all produced materials will be characterised by basic, standardized methods. During the Monitoring Meeting of January 2009, Mechanical testing was decided to be performed using the same specimen geometries for each test. These are standard specimens validated by FZK. Basic characterisation encompasses:

a) DBTT either by Charpy (KLST standard) or bending tests with different strain rates
b) creep/tensile/indentation at 1100-1300 °C
c) thermal conductivity
d) re-crystallisation temperature
e) microstructure analysis

2.3 Armour Materials Optimisation:

The goal is to optimise armour materials and high heat flux testing. Candidate materials have to be characterised by fatigue and shock tests under electrons or He/H beams for an assessment of their degradation and possible lifetimes.

Long term objectives :

- Industrial scale production of a refractory material for armour applications.
- Reinforcement by fibre composites (crack stopper).
- Full characterisation (including data base) of such a material.

Objectives for 2010:

Full joint metallurgical characterisation of the reference W-alloy ordered under Priority Support during the WP-2008-2009.
Basic screening of different commercial tungsten materials (rods and plates in different orientations). The goal is to characterise the influence of microstructure on properties during high heat flux load.

I. Material Optimisation/Production

a) Production of W-Y_2O_3 and W-TiC (on laboratory scale) tungsten materials by mechanical alloying or alternative technologies, powder mixing, pressing, sintering, and final cold/hot work.
b) Production of W-ODS materials on industry scale by powder injection moulding.
c) Production of oxidation resistant ternary W-Cr-Si and quaternary W-Cr-Si-Zr alloys in coating and bulk for FW protection (“low operating temperature”).

II. Material Testing

a) thermal fatigue tests in the high temperature range (T>1500°C)
b) thermal shock tests in the operation relevant parameter range
c) material characterisation in an extended high temperature range (basic properties)
d) thermal fatigue tests under hydrogen and/or helium beam loading with divertor relevant fluxes

2.4 Irradiation Performance

The present situation of the radiation damage induced by neutron irradiation can be characterised as follows:

- The W and W-alloys irradiated so far exhibit extreme brittleness, which discard these particular materials to be used as structural materials.
- A variety of medium dose/medium temperature irradiation experiments is under way within external programs (e.g. fission, EXTREMAT).
- The knowledge on irradiation induced embrittlement and He/H accumulation under divertor relevant conditions is rather rudimentary.
- Remaining questions: Does high dose neutron irradiation induce the shift of DBTT above 600°C, 1300°C, or further up the temperature scale? How does He/H production affect mechanical properties? What is the consequence of transmutation effects?

To address the question about the expected change (increase) of DBTT of tungsten, as a function of irradiation dose *and* irradiation temperature, it is proposed to launch an activity on the characterization of *radiation-induced hardening* of the reference tungsten batch material, by means of performing surface indentation tests on specimens irradiated with self-ions at JANNUS at various temperatures in the range between the room temperature and 800°C. The objective of these tests is to determine the characteristic (high) irradiation temperature at which the accumulation of dose produces no detectable hardening.

Long term objectives:

- Irradiation experiments at divertor relevant test conditions.
- Validation irradiation under fusion-like neutron spectrum in IFMIF.
- Medium temperature/high dose fast reactor irradiation in cooperation with external programs.

Objectives for 2010:

Collecting and evaluating irradiation data from external programs (EXTREMAT).

2.5 Materials Science and modelling:

The main objective for this area is to assist and guide the materials development process. The basic idea is to identify the origin of extreme brittleness of tungsten, to explore a range of potential ductilisation treatments, and to transfer the knowledge to the materials development area, with in parallel understanding and modelling radiation effects i. e. point defects and He&H accumulation in bulk and sub-surface.

Long term objectives:

- Providing knowledge on basic material deformation mechanisms which can assist the materials development work.

Objectives for 2010:

I. Plasticity Studies

a) micro-mechanic tests for characterising the influence of metallurgical factors on ductility.
b) identification of relevant ductilisation mechanisms in W-Re alloys.
c) Optimisation of severe plastic deformation method for tungsten materials

II. Theory, Simulation, Validation

a) Ab initio calculation in support to phase diagram calculation of W-Re (σ-phase), W-Ta, W-V and W-Ti systems
b) Ab initio based study of phase stability and radiation defect structures in Tungsten-Vanadium and Tungsten-Tantalum Alloys
c) Ab initio calculations of core structure and energetics of screw dislocations in W containing various elements such as Re, Os, Ta and V.
d) Ab initio energetics of He/H and point defects. Kinetic modeling of He and dpa accumulation in bulk and sub-surface.
e) Molecular dynamic simulations of the mobility of edge & screw dislocations and of their interaction with He vacancy clusters (irradiation hardening). TEM image simulations of irradiation-induced defects.
f) Microstructure analysis of He implanted tungsten and under dual-ion beam conditions. Characterisation by Positron Annihilation Spectroscopy and Nuclear Reaction activation.
g) In-situ TEM observation to study dislocation dynamics and interaction with radiation defects (in combination with multi-ion beam facilities).

3. Work Description and Breakdown

3.1 Work Breakdown

The breakdown of milestones and deliverables to achieve the objectives given above are detailed below.

It should be noted that for every programmatic line a Final Report is requested by December 2010 by the Principal Investigators presenting the main results and expressing recommendations for the scientific/technical follow-up of every line of the Research Project.

Activity (i): Fabrication Process Development		
Objectives	**Milestones**	**Deliverables**
Development of W-Eurofer and	**Dec. 2010**: First set of	• **Dec. 2010:** Intermediate

W-W joints (brazing & functional gradient)	alternative LA or RA braze alloys. Fabrication routes for property gradient joints W-EUROFER. Explosive bonding tests in plane geometry	reports: Screening results of RA or LA brazes. Development process in electrolytic & galvanic coatings. • **Dec 2010**: Intermediate report for property gradient joint and explosive welding between W & EUROFER
Investigating, characterising and developing fabrication, machining and mass production techniques (deep drawing, powder injection moulding, alternatives)	**Dec 2010:** Evaluation of progress and implications to divertor design	• **Oct. 2010:** Technical report: Advances in ECM, deep drawing and powder injection moulding • **Oct. 2010:** Technical report: Advances in machining and fabrication technologies

Activity (ii): Structural Material development		
Objectives	**Milestones**	**Deliverables**
Development and basic characterisation of tungsten base materials for structural applications	**Dec 2010:** Achievement of first characterisation of W-Ta, W-V and W-Ti alloys	• **Dec. 2010:** Final reports on basic characterisation W-Ti, W-V, and W-Ta warm or hot processed & severely plastically deformed for structure applications • **Dec 2010:** Intermediate report on W-V and W-Ti ODS materials: fabrication route & basic Characterisation

Activity (iii): Armour Material Optimisation		
Objectives	**Milestones**	**Deliverables**
Screening, optimisation, and thermal fatigue/shock testing of tungsten base armour materials	**Dec 2010:** achievement of testing the reference W-batch **Dec. 2010:** delivery of first materials for high temp. tests	• **Dec .2010:** Summary report on industrial PIM W-ODS produced materials • **Oct. 2010:** Summary report on mechanical and high temperature/heat flux characterisation (electron, He, H) of the W-reference batch. • **Oct. 2010:** First report on W-Y_2O_3, W-TiC, and W-Si-Cr mechanical and high temperature/heat flux characterisation (electron, He, H). • **Dec. 2010:** Report: Summary and recommendations for

		future work and implications for divertor design
Developing oxidation resistant W-Cr-Si and W-Cr-Si-Zr alloys in coating and bulk	**Dec. 2010**: Bulk materials fabricared	• **Dec 2010**: Report on oxidation resistant W-alloys: optimised microstructure & chemical composition, oxidation kinetics and test under heat flux and He&H beam.

Activity (iv): Irradiation Performance Testing		
Objectives	**Milestones**	**Deliverables**
Surface indentation testing of reference tungsten specimens, ion irradiated at JANNUS at temperatures between 27°C and 800°C, to find a characteristic irradiation temperature at which accumulation of dose produces no detectable hardening.	**Dec. 2010:** delivery of results of first experimental tests on hardening of ion irradiated reference tungsten specimens	**Dec. 2010:** Report: Feasibility study on radiation induced hardening of tungsten, ion irradiated at several irradiation temperatures, with indentation tests performed at room temperature.
Data collection and evaluation		• **Dec. 2010:** EXTREMAT status

Activity (v): Materials Science and Modelling:		
Objectives	**Milestones**	**Deliverables**
Plasticity studies and fracture mechanics with focus on impurities, texture, and Re effect.	**Dec. 2010:** First set of data on W-Ta as reference alloys for low temperature application.	• **Dec. 2010:** Intermediate report on microstructure and micro-mechanics characterisation of W-Ta, W-V, W-Ti
Defect calculations with ab initio, molecular dynamics, and dislocation dynamics.	**Dec. 2010:** first ab initio calculated formation enthalpy for phase diagram calculation of W-Re and W-Ta **Dec.2010:** Development of quantitative understanding of phase stability of bcc W-Ta and W-V alloys from low to high temperature regions, using density functional theory (DFT) calculations and cluster expansion **Dec.2010:** Investigation of the effect of Ta and V alloying on irradiated point defects (vacancies and self-interstitial atoms (SIA)) for a range of concentrations of alloying elements in W alloys.	• **Dec 2010:**Report on ab inito calculation of formation enthalpy in the W-Re phase diagram, including the σ-phase • **Dec 2010:** Report on the phase stability of W-Ta and W-V alloys in bcc phases at low and finite temperature regions by using DFT, Cluster Expansion and Monte-Carlo simulations, point defect (vacancy and SIA) calculations for W-Ta and W-V alloys, and investigation of migration pathways for point defects. • **Dec 2010:** Report on ab initio calculation of core structure, Peierls potential of screw

	Dec. 2010: first ab initio based OkMC prediction of dpa and He accumulation in bulk including mobility of small He-clusters He_2 & He_3. **Dec 2010:** Achievement of the ab initio data base of He-V clustering in sub-surface. Selection of the best kinetic tools to be adapted for sub-surface microstructure prediction	dislocation in W and interaction with Re, Os Ta, V & Nb • **Dec 2010:** Report on ab initio energies He_2 & He_3 clusters. Complement OkMC code. OkMC prediction of He & dpa accumulation in bulk for comparison with experiments. • **Dec 2010**: Ab initio calculation of the energies of He & V clusters close to low energy surface of W. • **Dec 2010:** Report on improving He-V and He-SIA interaction in present W-He potential. MD simulation of the He-W system for large scale modelling. Cascades & dislocations
Validation experiments (He/H behaviour in W, in situ TEM)	**Dec. 2010**: First set of characterised W metal after dual beam and dpa accumulation	• **Dec. 2010:** Report on microstructure obtained under dual beam and TEM characterisation. • **Dec. 2010:** Report on He and H co-implantation characterised by Positron Annihilation Spectroscopy (PAS) and Nuclear Reaction activation. • **Dec. 2010:** Report: Summary and recommendations for modelling and materials development

(vi) Priority Support:

All the activities described above are foreseen under Base Line Support except the following ones for which Priority Support are proposed. They are given in the table hereafter and concern:

- Project Coordination: 0.5PPY per year.
- High heat flux tests on optimised finger module mock-ups in Efremov Institute, Saint Petersburg, Russia (joint coordinated activity involving several Associations for post examination): 0.75 PPY, 100 k€
- The expenditure for Joint characterisation of the reference W-batch delivered in 2009 (1.5 PPY and 50 k€)

- Micro-plasticity studies and experimental validation of He kinetics and dislocation interaction by dual beam and in situ TEM to be carried out by several Associations for a joint effort of experimental validation of the modelling tools: 0.75 PPY and 90 k€

Activities	**Human Resources**	**Other Expenditures**
	2010	**2010**
Fusion Materials TG coordination	0.5	
High heat flux tests on optimised finger module mock-ups in Efremov Institute, Saint Petersburg, Russia (joint coordinated activity involving several Associations for post examination)	0.75	100
Joint characterisation of the reference W-batch delivered in 2009	1.5	50
Micro-plasticity studies and experimental validation of He kinetics and dislocation interaction by dual beam and in situ TEM (joint coordinated activity involving several associations)	0.75	90
TOTAL	**3.5**	**240**

3.2 JET related activities

Non applicable.

3.3 Publications

A list of publications produced on the basis of results of the 2010-WP, will be compiled after the completion of these tasks.

4. Scientific and Technical Reports

4.1 Progress reports

At the end of each calendar year and at intermediate times where appropriate, the Task Coordinator shall submit a report on activities under the Task Agreement to the EFDA Leader for his approval. These reports shall describe the progress made by each Association on each activity, and they shall indicate the level of achievement of the objectives, the status of the activities, the allocation of resources and recommendations for the next year where applicable. The EURATOM financial contribution will be made through the usual procedures for baseline support through the Contract of Association.

4.2 Report of achievements under Priority Support (final report and, when appropriate, intermediate reports):

The progress of tasks undertaken under Priority Support and the status of deliverables will be reported separately to the EFDA Leader. A final report (and intermediate reports indicating any substantial progress in the achievement of deliverables, if requested by the EFDA Leader) shall be prepared by the Task Coordinator and submitted to the EFDA Leader. These reports shall include specific sub-sections for each of the Associations involved. They shall document the degree to which the deliverables outlined have been achieved, and shall include a breakdown of expenditure for each Association. The EURATOM financial contribution will be made after approval by the EFDA Leader of these reports.

4.3 Milestones.

The results obtained within the Research Project Tungsten and Tungsten Alloys Development will be presented by the principal investigators and reviewed during joint monitoring meetings held twice a year. On this basis the progress accomplished by the contributing Associations will be reported by the Coordinator to the EFDA Leader.

The report on the Association activities under Priority Support will be prepared by the Coordinator to be presented to the EFDA Leader at the end of every calendar year.

The final and technical report will be submitted to the Responsible Officer of the Topical Group for approval and uploading the IDM database.

5. Association Proposal

The Associations are requested to complete the Association via ECoM system.