Brief Summary of the Workshop
Challenges to Developing W-Based Materials for Fusion Applications

February 13-15, 2012
UC Santa Barbara

G. R. Odette (UCSB), R. Kurtz (PNNL), R. Nygren (SNL), J. B. Wirth (UT), Marion (LLNL)

Overview

- G. R. Odette organizer with enormous help from M. Reith
- Thirty six participants – 24 US, 1 Japan, 11 Europe (KIT 5, Garching 1, Juelich 1, Leoben 1, Oxford 2, Plansee 1, Tohoku U 1)
- US DOE & Labs 12, universities 10, SBIR companies 2
- Five topical sessions with seven 40-50 minute and twenty 15-20 invited presentations plus large block of time for discussions and a final session for summaries and conclusions
- Most presentations were on suggested topics to achieve balance and comprehensive coverage
- CD meeting record

Challenges to Developing W-Based Materials for Fusion Applications

2/13-15/2012 UC Santa Barbara, Santa Barbara, CA
CNSI Ealings Hall Room 1601

	REGISTRATION	7:45-8:25 am
Monday am	Title	Time
R. Odette	Welcome and introduction to the workshop objectives	8:30-8:40 am
P. Pappano	DOE welcome	8:40-8:45 am
Chair: J, Konys; Discussion Facilitator: D. Youthison	**Design and Service Requirements**	
M. Rieth	Tungsten - An overview of general properties and possible structural applications in fusion power plants	8:45-9:35 am
T. Loewenhoff, J. Linke, G. Pintsuk and M. Wirtz	Impact of thermal fatigue and thermal shocks on plasma facing components	9:35-10:00 am
	Discussion	10:00-10:30 am
	Break	10:30-10:50
R. Nygren, M. Tillack and J. Blanchard	Thermomechnical loading and observed failure mechanisms in PFC	10:50-11:15 am
Ch. Linsmeier, F. Koch, J. Brinkmann, H. Greuner, H. Maier, S. Lindig, M. Balden and M. Rieth	Tungsten materials for a fusion reactor first wall: self-passivation and high H/He particle flux effects	11:15-11:40 am
R. Odette and J. Heathcote	Test methods, size effects and principles of ductile phase composite toughening	11:40-12:00
	Discussion	12:00-12:30 pm
	Lunch	12:30-1:30 pm

Chair: S. Matsuo; Discussion Facilitator: R. Kurtz	**Processing and Fabrication**	
W. Knabl	Commercial Tungsten products - properties, applications, fabrication and processing	1:30-2:20 pm
J. Reiser, M. Rieth, B. Dafferner, A. Hoffmann	Deep drawing, brazing, design, mockup fabrication	2:20-2:40 pm
	Discussion	2:40-3:10 pm
T. Yamamoto, A. Kimura,…	Bonding and bond failure-debonding observations and mechanics	3:10-3:30 pm
	Break	3:30-3:50 pm
S. Antusch and V. Piotter	Powder injection molding, W armor and mockup fabrication	3:50-4:15 pm
W. Krauss, J. Konys, N. Holstein and J. Lorenz	Electro-chemical processing for tungsten fabrication and joining by layer deposition	4:15-4:40 pm
E. Ohrinre and R. Dehoff	Electron-Beam Additive Manufacturing of Tungsten Materials for Fusion	4:40-5:00 pm
	Discussion	5:00-5:30 pm

Chair: R. Nygren; Discussion Facilitator D. Armstrong	**Mechanical Behavior, Advanced Alloys and Composites**	
R. Pippan, S. Wurster, B. Gludovatz, H. Li and L. Romaner	Fracture toughness controlling phenomena in W and W alloys.	8:30-9:20 am
S. Matsuo and H. Kurishita	Fine Grain Precipitate Stabilized, Recrystallized W-Alloys	9:20-9:40 am
	Discussion	9:40-10:10 am
T. Crosby and N. M. Ghoniem	Thermo-mechanical and damage mechanics modeling of W divertors	10:10-10:30 am
	Break	10:30-10:50 am
J. Reiser, M. Rieth, B. Dafferner and A. Hoffmann	W laminate composites	10:50-11:10 am

Tuesday PM

Chair: J.Marion; Discussion Facilitator: J.P. Allain	**Bulk and Surface Irradiation Effects**	
S.A. Maloy and T.J. Romero	Irradiation Induced Microstructures and Hardening in W-alloys	1:30-2:15 pm
L L Snead, T S Byun and T. Yamamoto	Irradiation Effects in and US irradiation Facilities for Tungsten	2:15-2:40 pm
	Discussion	2:40-3:10 pm
	Break	3:10-3:30 pm
R. Doerner, M.J. Baldwin and the PISCES Team	Plasma interactions with W surfaces	3:30-4:20 pm
B.D. Wirth, T. Faney, K. Hammond, N. Juslin, F. Sefta	Multiscale materials modeling of low-energy He plasma surface interactions with tungsten	4:20-5:00 pm
	Discussion	5:00-5:30 pm

Wednesday am

Chair: T. Yamamoto; Discussion Facilitator: G. R. Odette	**Modeling**	
S. Roberts and Dave Armstrong	Fundamentals of brittle fracture and the BDT in W and microscale tests	8:30-9:20 am
J. Marion, T. Hoang, S. Queyreau, V. Bulatov and R. Odette	Modeling bulk radiation damage and hardening in W-alloys	9:20-9:45 am
	Discussion	9:45-10:15 am
	Break	10:15-10:35 am
N. Juslin and B. D. Wirth	Defect modeling in W	10:35-11:00 am
W. Setyawan and R. J. Kurtz	Ab Initio Study of Grain Boundary Properties of Tungsten Alloys"	11:00-11:25 am
G.D. Samolyuk, Y.N. Osetsky and R.E. Stoller	First-priniples modeling dislocation-solute interactions in W	11:25-11:50 am
	Discussion	11:50-12:20 am

Tungsten – An overview of general properties and possible structural applications in fusion power plants

M. Reith

- Overviews basic properties, production routes, processing techniques and divertor applications and design
- Tungsten cannot be easily used for cooling structures since there are many different simultaneous requirements necessitating a set of simple design rules - applied to three helium cooled designs. Some conclusions
- Design windows are narrow at best.
- Ductile monolithic W probably cannot be achieved.
- Thin plates (<4 mm) of pure W (including small amounts of grain stabilizers seem to be the most suitable semi-finished products for structural applications (if at all).
- The best that can be done for monolithic W is to exploit anisotropic microstructures aligned to the load contour of the parts by deep drawing or bending of plates.
- Copper could in principle be used as brazing material for W-steel joints but needs additional strengthening
- Suitable structural W-W joints are not yet demonstrated and characterized.
- W irradiation data is needed.
- Determination of the lowest possible operating temperature is very important and of highest priority.

Impact of thermal fatigue and thermal shocks on plasma facing components

T. Loewenhoff et al.

The most mature concept, a tungsten monoblock design, survived 1000 cycles at 18 MW/m2 without degradation, even after an ITER relevant neutron irradiation of 0.6 dpa.

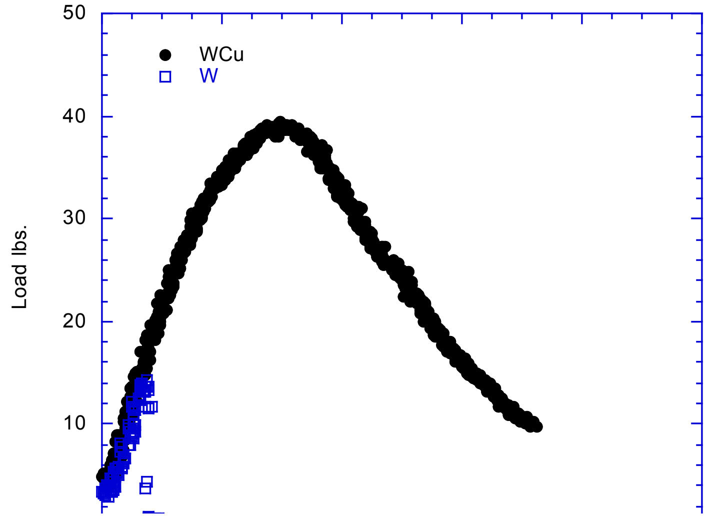
High pulse number (≤ 106, ITER relevant) tests show a damage threshold of < 0.27 GW/m2 for pure tungsten (grains oriented parallel to the surface) at base temperatures up to 700 °C.

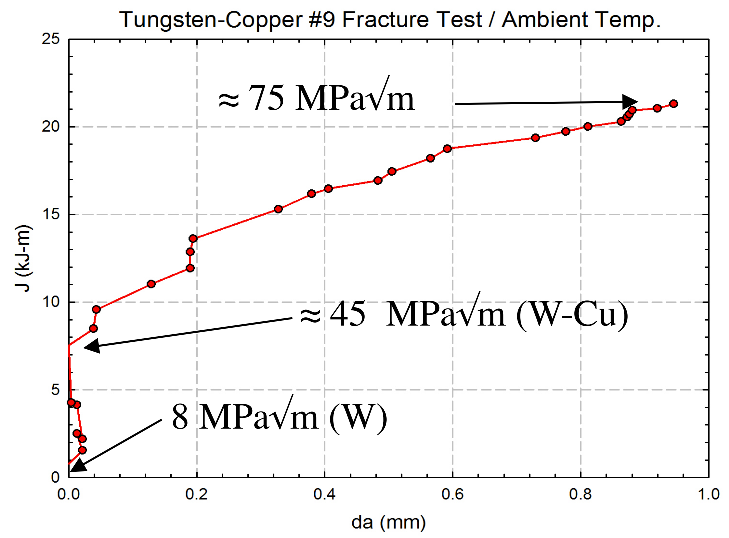
Open issues are the performance under high cycle transients after/during neutron irradiation, after recrystallization and under simultaneous particle flux (D/T/He).

For DEMO new heat removal technologies will be necessary, as well as investigations at much higher neutron doses of ~20 dpa.

Test methods and principles of ductile phase composite toughening
G. R. Odette et al.

- Developed a pre-crack test protocol for W - K_{Jmax} = 8.3±0.45 MPa√m
- Model composite W-28 wt.% Cu
- Three point bend J-da tests
- Nominal K_{Jm} = 24.9±3.5 MPa√m
- Extensive stable crack growth and slow load drop
- Initiation and maximum measured K_r – 45 to 75 MPa√m
- Large increase in strength and ductility vs. W due to ductile phase toughening by bridging with well-developed mechanics-design model





Processing and Fabrication

1. **Commercial Tungsten Products: Its Properties, Applications, Fabrication and Processing**
   - High melting point
   - Low coefficient of thermal expansion
   - High density
   - High thermal conductivity
   - Excellent resistance against corrosive media (acids, liquid salts and metals, glass

- Important issues – ductility, fracture toughness, and recrystallization behavior, volatile oxides low solubility of O, N, H.
- Ductility controlled by stress state, deformation rate, subgrain size & shape, dislocation structure, interstitial and substitutional impurities, and grain boundary segregation.
- Powder metallurgy only viable production route, only possibility to add dispersoids, finer grain structure after sintering compared to mold products.
- Joining methods: fusion welding, solid state welding, brazing soldering.
- Machining pure tungsten is difficult.

2. **Deep drawing, brazing, design, mockup fabrication**

- Deep drawing is of interest because it may be the only fabrication process that allows the microstructure to be properly aligned.
- Proof of feasibility of deep drawing.

3. **Bonding and bond failure- debonding observations**……

- Objective to develop high performance ODS and RAFM self-joints.
- Develop and evaluate irradiation performance of dissimilar joints such as W coatings to ODS, RAFM, etc.
- Explore synergistic effects of neutrons, helium and tritium on mechanical properties.

4. **Powder injection molding, W armor …**

- 50 % vol organic binder (polymer): suitable to complicated geometries.
- 3-step process: debinding (500°C), sintering (1800°C), HIP (2100°C, 250MPa).
- Ultimate goal is to develop fabrication technology for relatively thin section armor for first-wall, divertor.

5. **Electro-chemical processing for fabrication & joining**

- Feasibility of fine structuring W surface by EDM.
- Electro-chemical deposition of brazing layers (Cu-Pd).
- Deposition of W layers by ionic liquids.

6. **Electron-beam manufacturing**

- Scoping study to explore the potential use of electron beam additive manufacturing to produce graded W coatings or layers.
- Very early stage of study exploring a range of process variables with metallographic and micro-analytical examinations to be performed.

Challenges to Developing W-Based Materials for Fusion Applications

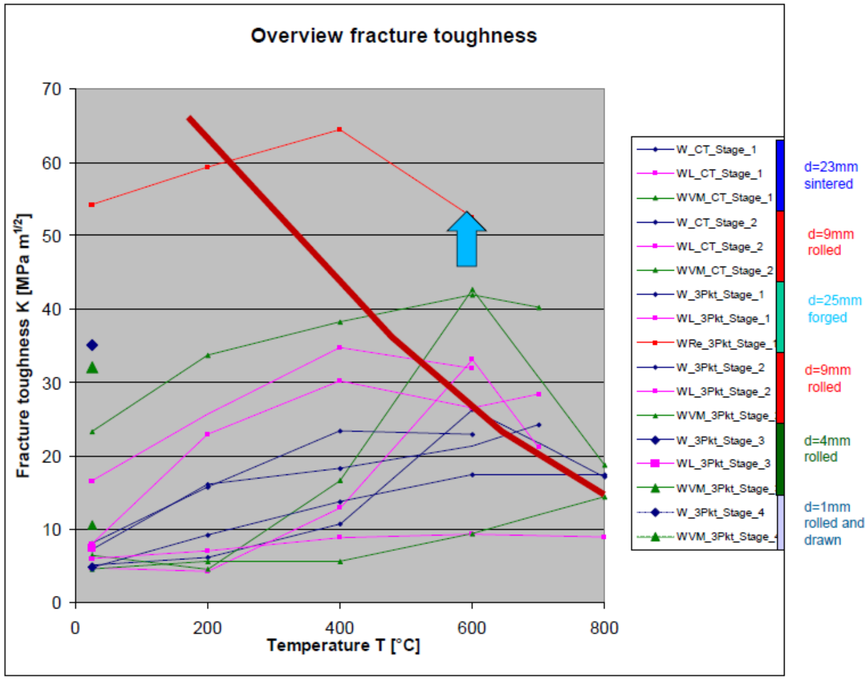
Tues AM Mechanical Behavior, Advanced Alloys & Composites

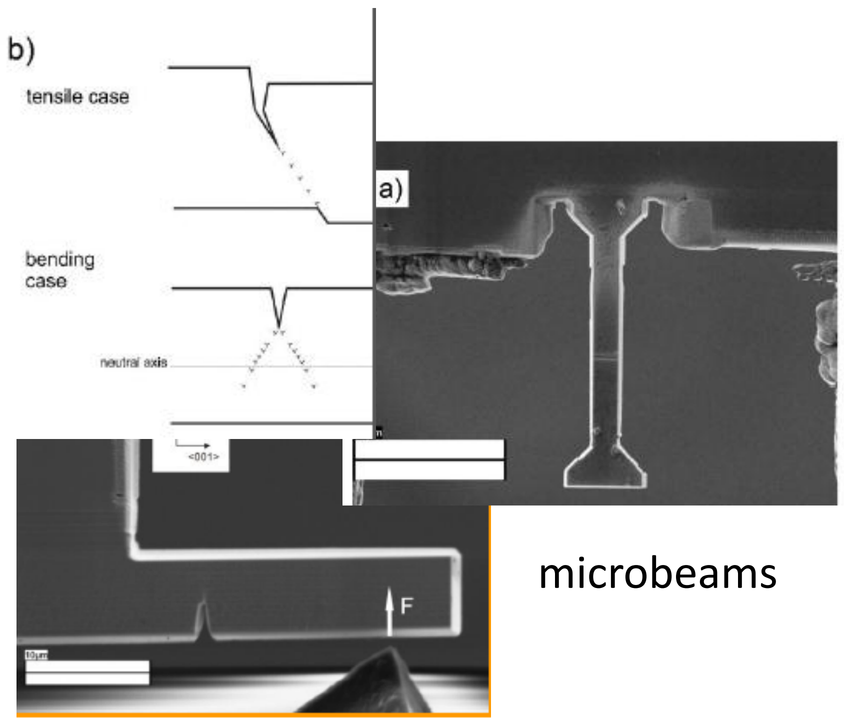
Chair: R. Nygren; Discussion Facilitator D. Armstrong

Fracture toughness controlling phenomena in W and W alloys	Matsuo & Kurishita
Thermo-mechanical and damage mechanics modeling of W divertors	Crosby & Ghoniem
W laminate composites	Reiser, Rieth, Dafferner & Hoffmann
Fiber-reinforced composites with enhanced mechanical properties	Linsmeier, You, Riesch, Du, Höschen, Brendel, Paffenholz, Herrmann, Schöbel, Kimmig, Scheel & Bolt
Processing and Irradiation Tests on Multimodal and Nanostructured Tungsten	Allain, El-Atwani, Neff & Klenosky
Near Net Shape Formed Tungsten Components and Coatings for Fusion	O'Dell, McKechnie, Shchetkovskiy & Smirnov
Plasma Spark Scintering of W	Singh

Fracture toughness controlling phenomena in W and W alloys – Pippan et al.

- Tremendous amount of information
- Contrasted W-Re alloys and pure W. e.g., ….. the real difference is in the amount of deformation near grain boundaries. For W26B there is a zone ~10 microns along crack where there is deformation.
- theoretical analyses of screw dislocations and Pierl's stress … core structure of the dislocations. … e.g., W-Re has strong asymmetry in core, W and W-Ta have a symmetric core. General conclusion: Ta family no help for improving W ductility
- For W-Re family, super-cell calculations at Juelich … how much Re (& other elements) attract dislocations. The values were high for Ir, then Os, Re, Mn.
- Nano-grained materials recrystallize at ~800C. K-doping can raise $T_{recrystallize}$ up to maybe 1200C. But … shape of grain is the most important feature. Round grains are preferable to oblong pancakes.





microbeams

Fine Grain Precipitate Stabilized, Recrystallized W-Alloys - Matsuo & Kurishita

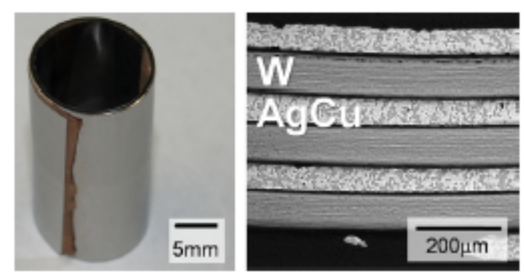
Grain boundary sliding modification. W-(0.25-1.5wt%)TiC. Use H instead of argon in glove box (mixing) to avoid Ar bubbles in ball milling. Result is ultra-fine grain with 80% random orientation of grains, size ~0.1 micron … but insufficient GB strength. Use superplasticity in compression of ~80% (compress disk to 20% height) to modify GBs. Treatment leads to increase in grain size about 10X but still fine grained.

Thermo-mechanical & damage mechanics modeling of W divertors - Crosby & Ghoniem

Multi-physics model: (a) He induced damage, (b) temperature transient induced damage. ….. map of cracking and damage on plot of Energy Flux vs Energy Density. He bubbles near surface, also sub-surface effect well beyond range. Model results show heavy concentration of field variables along grain boundaries which indicates that crack will go along boundaries. Thermal transient creates more damaging effect than He.

W laminate composites - Reiser, Rieth, Dafferner & Hoffmann

Possible approaches to make W ductile: 1) particles, fibers, or 2) laminated structures. … combined foils to make a laminate 3x4x27mm with W layers and AgCufoils between them. We analyzed the foil texture with recrystallized structure at several temps.



Fiber-reinforced composites with enhanced mechanical properties – Linsmeier et al

W lamellae on CuCrZr tube for a high heat flux test in GLADIS (dual ion beam at IPP) Stress analysis for 10 MW/m^2 → 5% strain in tube, and reinforcement needed … also case with intermediate Cu block with SiC fibers between CuCrZr and the W armor. The metal matrix composite behaved well but failure occurred near interface with W … inadequate cleaning of surfaces before joining. … also multi-layering with varying amounts of W in Cu layers .. tube-in-lamellae mockup, HHF testing 10.5 MW/m^2.

W fibers in W to deflect cracks. … ZrOx coating for interface, drawn W wire fibers, infiltrated W host using CVD. … Again, HHF tests in GLADIS were performed.

Processing & Irradiation Tests on Multimodal & Nanostructured W – Allain et al

PMF applications, PSI issues and the capabilities of PRIHSM work station at Purdue. … generate multi-modal microstructure with some <1 µm grains and larger grains. He irradiations of multi-modal and UFG W using 200eV He (below sputtering). Rich microstructural development was apparent in the small grains.

Near Net Shape Formed Tungsten Components and Coatings for Fusion - O'Dell et al

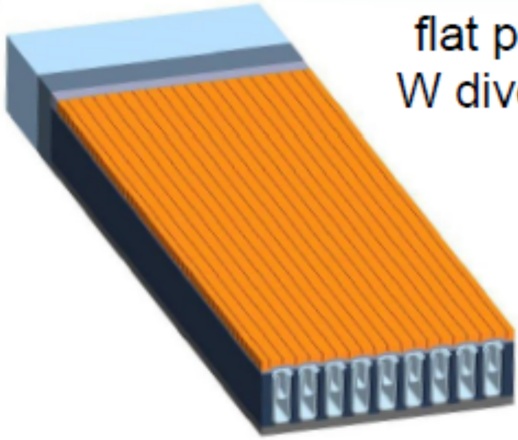
9 electrolyzing units … process called El-FormTM to make relatively large forms … 3 large vacuum plasma spray units. .. fabrication of T-tubes for HHF testing.

Plasma Spark Scintering of W - Singh (ARL, Penn State)

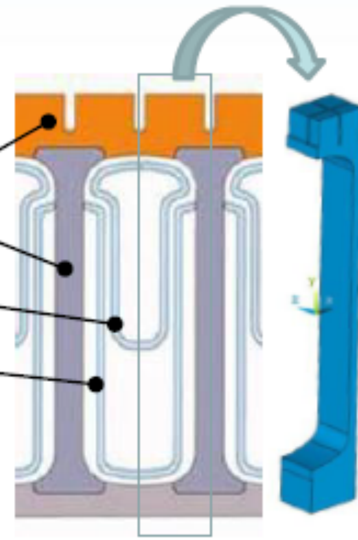
process for field-assisted sintering technology (FAST) and its use in various scintering processes and applications. Small amounts of WC.

W Plate Divertor: Crack, Stress Intensity

Work by Prof, Jake Blanchard, U. Wisconsin *p1 of 4*



flat plate
W divertor



Temperature

11 MW/m^2

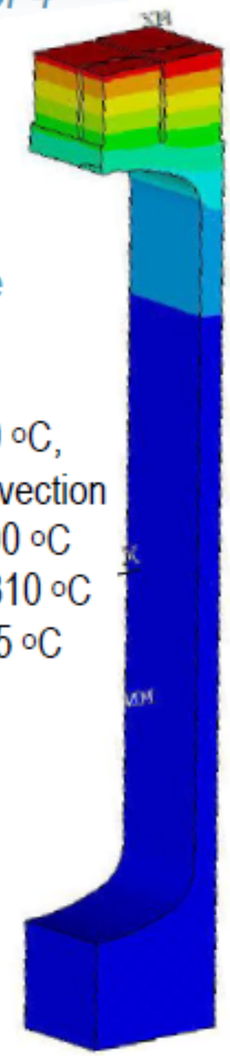
17.5 MW/m^3

10 MPa He, 600 °C, simplified convection

Max. T_{armor}= 2000 °C

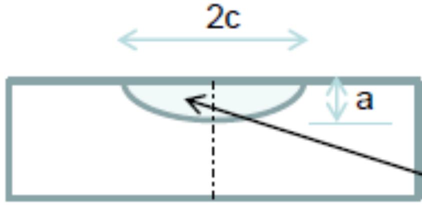
Max. $T_{structure}$=1310 °C

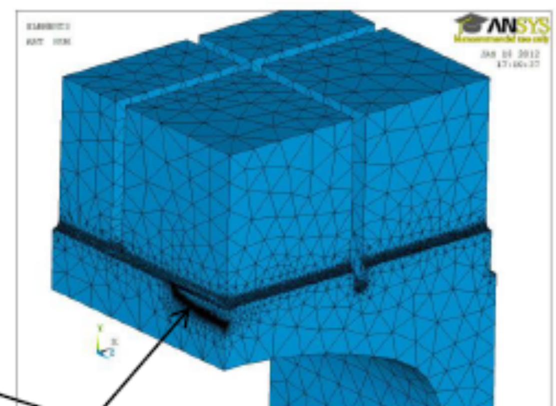
Min. $T_{structure}$=725 °C



Evaluate stress intensity factors

- Compare 3-D with 2-D plane stress or plane strain
- uncracked stress state
- PFC while heated
- PFC after cool-down





Crack Face

ARIES Team

UC San Diego

CER Center for Energy Research

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

W Plate Divertor: Crack, Stress Intensity, Blanchard, U. Wisc. *p4 of 4*

conclusions

- Intensities for 3-D models significantly lower than 2-D results (shutdown, plasma side crack)
- Critical crack is on inside surface of coolant channel
- Stress intensity is highest at full power
- 2-D modeling is overly-conservative

data needs

- Fracture toughness of tungsten
  - *As-manufactured*
  - *at temperature*
  - *irradiated*
- Crack growth rates
- Creep rates
- Creep rupture data
- Creep-fatigue interaction data

Bulk irradiation effects in W

- Maloy reviewed available neutron irradiation data on W and W-Re alloys, significant strength increases (200-500 MPa) at low dose (~1 dpa) which continues to increase with increasing dose (up to ~20 dpa)

- Strength increases are accompanied by substantial decreases in ductility

- Hardening and embrittlement appear more significant in W-Re alloys (note transmutation to Re in fusion neutron environment of pure W)

- Snead reviewed possible irradiation facilities for obtaining data, which include:
  - HFIR rabbit tubes
  - Possible Fusion Materials Irradiation Test Station (FMITS) at SNS
  - Possible MTS at LANL

- Future efforts evaluate potential for alloying improvements/W-ductile reinforced composite materials

Plasma Surface Interactions in W

- Doerner reviewed plasma surface interactions in W observed in laboratory devices (predominately PISCES-B), which reveals:
  - Impact of mixed D/He plasma exposure on D permeation/retention
  - He bubble formation near surface
  - 'Fuzz' formation, which may bring additional PMI problems (arcing, dust formation)
  - Opinion that the "operational issues with loss of W from the PFC surface due to plasma contact (including transient events) is likely to be the bigger issue. Plasma modifications may dominate the behavior of the material, compared to the original engineering of the tungsten."

- Wirth reviewed the initial modeling efforts to evaluate He/H plasma exposure on W & reiterated the plasma re-deposited nature of a PFC surface {Figure of Merit: anticipated sputtering yields >> $O(10^6$ /year)}
  - Krasheninnikov continuum model of He bubble inducing W flow & finger formation
  - He sub-surface bubble formation, bursting driving W self-interstitial emission that initially roughens surfaces

Modeling bulk irradiation effects in W

- Modeling efforts aimed primarily at understanding He effects in pure W.
- Becquart et al have carefully modeled 800-keV He-ion implantation experiments in single W crystals using kMC. They claim good agreement is obtained.
- Marian et al have simulated (fast) neutron irradiation in polycrystalline pure W and have looked at spectral (He) effects using (stochastic) mean-field rate theory.
- Still lacking capabilities to model the behavior of irradiated W-Re alloys (whose long-term microstructural evolution is governed by subsaturated Re precipitation).
- Future efforts geared toward developing thermodynamic models for irradiation-induced precipitation in W-Re alloys to study swelling suppression and hardening increases.

Modeling mechanical and fracture properties of W

- Roberts et al (Oxford) have modeled the brittle-to-ductile transiton in W. They find that it is controlled by (screw) dislocation mobility.
- Impurities (solutes) have a strong effect on fracture toughness and current modeling efforts are aimed at establishing whether this effect is governed by dislocation-solute interactions or intergranular cohesion.
- Groups at Univ Leoben (Austria) and ORNL have done fundamental DFT calculations of the effect of impurities on screw dislocation core structure. Ductilizing effect via Peierls stress established.
- Marian et al (LLNL) have obtained dislocation mobilities using MD simulations. MD not satisfactory to reproduce low strain rate behavior. Currently other methods to measure dislocation velocities are being explored.
- Setyawan et al (PNNL) have examined the effects of a large number of transition metal solutes on grain boundary (GB) cohesion using DFT methods. Their results show that GB cohesion is sensitive to *d*-orbital occupation with respect to the atomic environment in the GB plane.