Development of Tungsten Material for Fusion Reactor Applications

A RESEARCH HIGHLIGHTS PRESENTATION
TO DOE FUSION ENERGY GROUP
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THE UNIVERSITY OF UTAH

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Outline

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- Background – fusion reactor
- Background – tungsten alloys
- Technical approach
- Development of processes
- Results to Date
- Summary

Background

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W Components in Tokamak Fusion Reactor:

- **Part 1"First Wall":** Protection layer above the steel plasma facing inner surfaces of the blanket boxes.
- **Part 2 and 3 "Divertor":** Cooled target plates and the attached pressurized tubes for helium exhaustion.

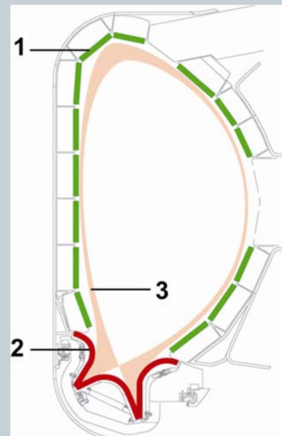

Figure from: M. Rieth et al. / Journal of Nuclear Materials 432 (2013) 482–500.

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Background

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Requirements for the First Wall:

1) stabilize during thermal annealing,
2) high radiation resistant,
3) high temperature oxidation resistant.

Requirements for the Divertor:

1) high thermal conductivity,
2) high temperature strength and stability,
3) high recrystallization temperature,
4) enough ductility under neutron load.

Reference: M. Rieth et al. / Journal of Nuclear Materials 432 (2013) 482–500

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How to improve ductility of W

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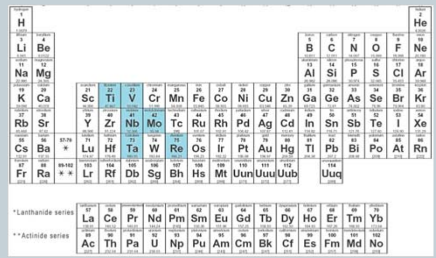
Alloying Introduced Ductility in W

- Re alloying is known to ductilize W by lowering the Peierls stress and introduce slip planes.[1]
- Some of the DFT studies suggested improvements in W's ductility by other solid solution elements such as Ta and Ti.[2]
- Bulk W-Ta alloy showed a high yield stress of ~3 GPa when loaded in quasi-static uniaxial compression.[3]



[1] H. Li et al. / Acta Materialia 60 (2012) 748-758.
[2] M. Muzyk et al./ Phys. Rev. B 84 (2011) 104115.
[3] R. T. Ott et al./ J. Mater. Res. 23 (2008) 133-139.

How to improve ductility of W

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Nanocrystalline W:

Ultrafine grain size introduces new deformation mechanisms like grain boundary sliding and enhanced grain rotation.

- Room temperature brittleness of W with grain size less than 300 nm decreased significantly. [1]
- W-2Y_2O_3 material with mean grain size of 1 µm became ductile at 673 K and above. [2]
- W-1.1TiC prepared using superplasticity-based microstructural modification process showed appreciable bend ductility at room temperature.[3]

[1] M. Faleschini et al. / Journal of Nuclear Materials 367–370 (2007) 800–805.
[2] M. Battabyal et al./ Material Science Engineering A 538 (2012) 53.
[3] H. Kurishita et al./ H. Journal of Nuclear Materials 398 (2010) 87.

How to improve ductility of W

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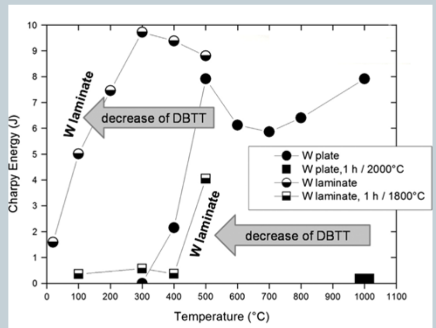
W Composites:

- The ductile properties of W foils could be expanded to bulk W by making laminate structure.[1]
- The wire-reinforced W composites demonstrated a potential benefit on material toughness.[2]



[1] S. Wurster et al. / Journal of Nuclear Materials 442 (2013) S181-S189.
[2] J. Du et al./ Compos. Sci. Technol. 70 (2010) 1482.

Technical Approach

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- **Nanostructure W**
  Decrease crystalline size and prepare nanostructure W materials by the novel high energy planetary milling, warm compaction, and low temperature high pressure sintering.
- **Alloying W with solid solution elements**
  Substitute expensive Re with Ta, V or Ti in W alloy with similar ductile property and much lower price.
- **Combination**
  Combine the nanostructuring and solid solution alloying to achieve a optimum W material with superior performance and reasonable cost.

Challenges of making nanocrystalline W

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Top down approach:

- Severe plastic deformation including the ECAE
- Good research techniques, cannot be used for production of components

Bottom up approach:

- Sintering and consolidation of nanosized W powder
- Rapid grain growth during high temperature sintering,
- Challenge: achieve high density, fine grain size

Unique Processes

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Project Goal: Achieve near-full densification with minimum grain growth

Synthesis and consolidation processes to achieve the goal:

- High Energy Planetary Ball Milling
- Warm Compaction,
- Low Temperature Sintering in Hydrogen
- Modified Rapid Omni-Directional Compaction.

Unique Processes

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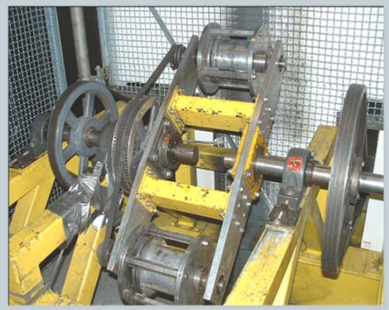
- High energy planetary ball milling
- 100 g centrifugal force
- Making 10-30 nm powder in 4 hours
- Enhanced sinterability of W, enabling sintering at relatively low temperature to achieve near-full densification with minimum grain growth



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Unique Processes

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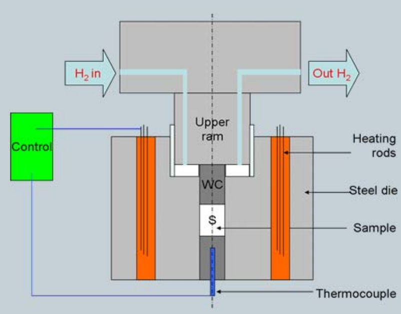
Warm compaction:

- Higher green density beneficial for full densification while minimizing grain growth
- Nanosized powder notoriously difficult to compact, usually low green density (30-40%)
- **Warm Compaction** process designed to compact nano W powder at moderate T to achieve higher green density (40-60%)



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Unique Processes

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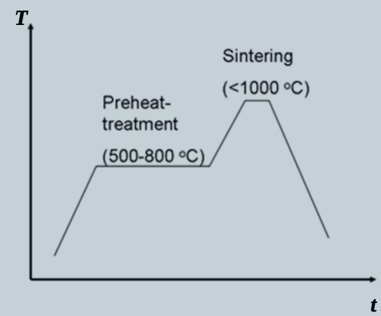
Low T sintering in H2

- Typical sintering T for W: >2000 C.
- Grain growth largely a function of the sintering temperature.
- This process: sintering at 1100 C to minimize grain growth, which achieving 98% densification.
- Possible only because of the nanosized powder made from the high energy planetary ball milling process.



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Unique Processes

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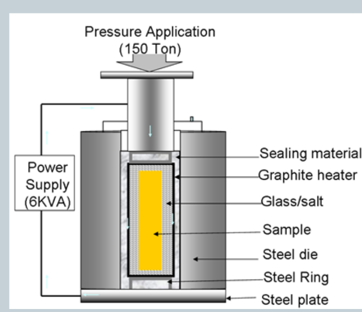
Rapid Heating Omni-directional Compaction

- To remove remaining porosity (2%) after sintering in H2
- To avoid excessive grain growth, low T is necessary
- The RhOC process:
  - Rapid heating to 900 – 1400 C
  - Pressures up to 1GPa.
  - Isostatic pressure



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Results to Date

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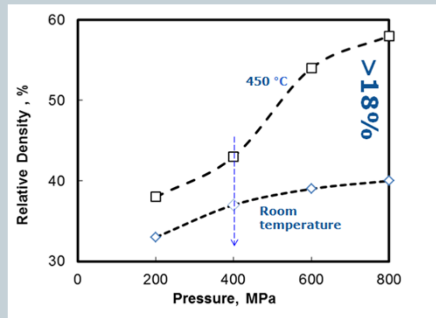
Warm Compaction:

- Compaction performed above DBTT of nano W powder leads to a 18% increase in the relative density.



Results to Date

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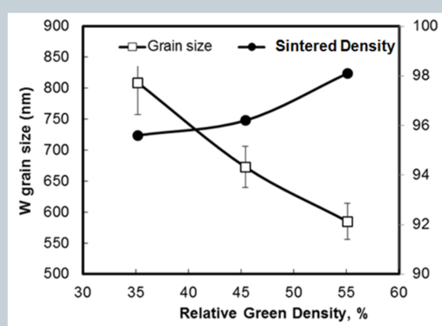
Warm Compaction:

- Higher green density leads to higher sintered density and smaller grain size



Results to Date

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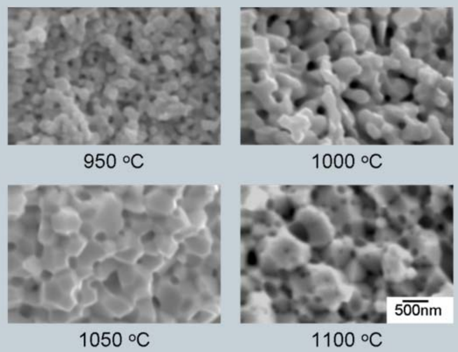
Low temperature sintering in H2



- The lower the sintering temperature, the smaller the grain size in the sintered material.

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Results to Date

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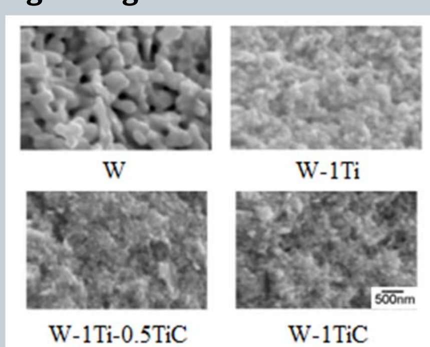
Effects of grain growth inhibitor



- During sintering at 1000 ºC, the addition of second phase particles to tungsten impedes the mobility of the grain boundaries and controls the grain growth.

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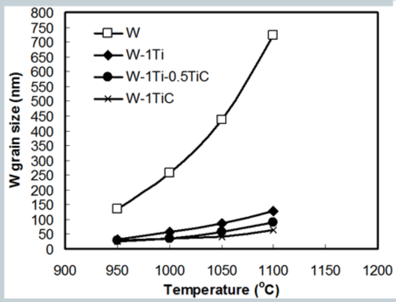
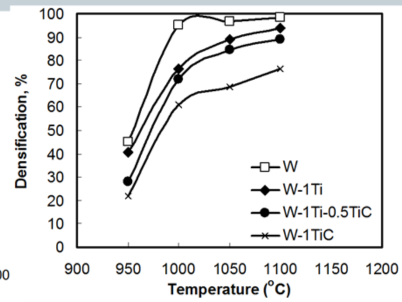
Results to Date

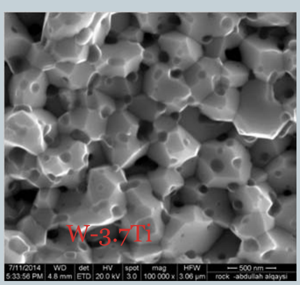
Effects of grain growth inhibitor

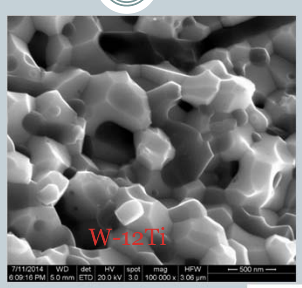




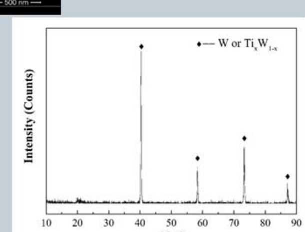
- Grain size and densification increase as function of temperature during sintering
- Second phase particle decreases grain size but also decreases the densification.

Phase analysis





The XRD pattern of as sintered W-12Ti alloy



Results to Date

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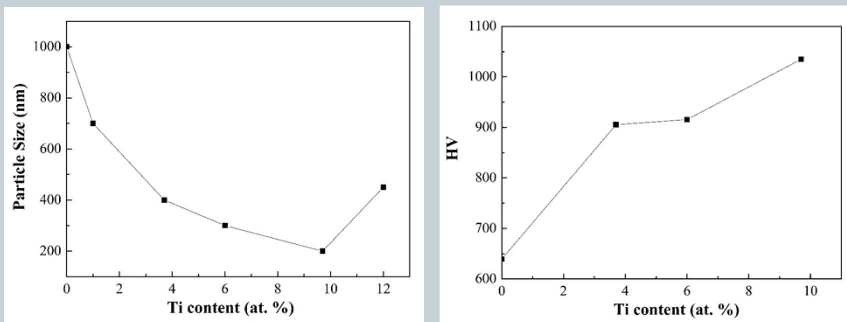
Grain Size & Vickers-hardness



The grain size and hardness of as-sintered W-Ti alloys

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Results to Date

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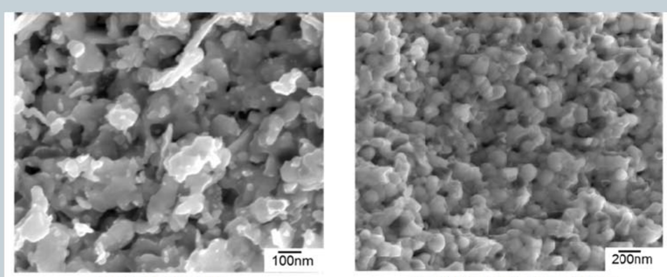
Effects of RhOC



W-1TiAl, 1000C-1h
Density > 85%, Grain Size < 100nm

W-1TiAl, 1000C-1h+m-ROCed
Density > 98%, Grain Size < 90.6nm

- The RhOC process further increases the material's density with only limited grain growth.

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Results to Date

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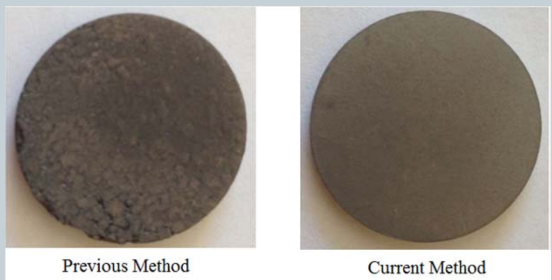
Fabrication of discs for permeation test



- The improved powder preparation and de-lubrication methods decreases the possibility of crack formation during sintering.

Summary

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- A unique set of processes developed for making ultrafine grain W materials with near-full or full density and <200 nm grain size
- Effects of grain growth inhibitors systematically studied
- Mechanical properties yet to be evaluated
- Prepare samples for H_2 isotope permeation tests and irradiation tests?

Acknowledgement

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