Measuring Residual Strain after Hot Isostatic Pressing of ISIS Target Plates

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Overview

• Background
• ISIS target manufacture
• Asymmetric-clad strip method
• Results and analysis
• Future plans
• Implications for target design
Acknowledgements

• Experiment concept – Peter Loveridge
• Sample manufacture – Jeremy Moor, Max Rowland
• Management – Ste Gallimore, David Jenkins
Background

• ISIS operates two spallation targets; TS1 and TS2
  – Both have tungsten cores clad in tantalum for corrosion resistance
  – Any significant cladding breach means we have to replace the target
    • Causes activation of the cooling plant, which needs hands-on maintenance

• Cladding is attached by Hot Isostatic Press (HIP)
  – Produces a strong bond with good thermal contact
  – High residual stress expected from HIP – more than from beam heating
  – Exact amount of residual stress is a major unknown in current simulations*

ISIS Target Manufacture

- Tantalum can be welded shut with tungsten core inside
- Hot Isostatic Press (HIP) process applies high temperature and pressure, bonding cladding and core
- Final machining to achieve dimensional accuracy
- Plates welded together to form target stack (TS1 Only)
ISIS Target Manufacture

• HIP cycle in detail:
  – Cladding deforms plastically under high pressure (140MPa)
  – Peak temperature is 1200°C, held for 2 hours; this relieves stress, but does not cause grain growth
  – Tantalum and tungsten are bonded together
  – As the clad target cools below the annealing temperature, residual stress builds up due to different coefficients of thermal expansion:
    • Tungsten 4.5E-06/K
    • Tantalum 6.3E-06/K

A typical ISIS HIP cycle
ISIS Target Manufacture

Simplifying assumptions for calculating residual stress:

- All stress from welding and HIP pressure is relieved during HIPing
- Stress due to final machining and plate welding is small compared to stress from HIPing, and can be ignored
- Stress from HIP cooldown is relieved at first, but below a certain ‘lock-in’ temperature stress starts to builds up
  - Industry uses a stress relieving temperature of around 850°C
  - Lock-in temperature estimated to be 500°C, but this needs validation
Asymmetric-Clad Strip Method

- Provides a simple, mechanical method of measuring residual stress after HIPing
  - HIP a long strip of tungsten with asymmetric tantalum cladding
  - The strip will deflect in proportion to the residual stress
  - A parametric FEA study was used to find the optimum dimensions to produce a measurable deflection without breaking the sample

Nominal dimensions of asymmetric-clad strip
Theory

• Behaviour is similar to a bimetallic strip after a temperature change

• We expect stress to be tensile in the cladding and compressive in the core
  – Curvature should be concave on the thick tantalum side

• Should deflect with the same radius of curvature in both directions, forming part of a spherical surface
Simulation

- FEA simulation using ANSYS Workbench
  - Includes bilinear model for tantalum plasticity
  - Deflected surface is nearly spherical, as expected

Quarter symmetry model and mesh

Out of plane deformation result for 200MPa yield, 500°C lock-in
Simulation

- The deflection result depends on two unknowns: lock-in temperature and tantalum yield strength
  - Deflection is roughly proportional to lock-in temperature, with a change in gradient when yielding occurs

![Simulated Deflection](image1)

![Simulated Radius of Curvature](image2)
Manufacture

- Manufactured by Jeremy Moor and his team using the same materials and methods as ISIS targets
Measurement

- Sample was measured before and after HIP using a Faro Edge arm (laser scanner coordinate measuring machine)
  - Concave on upper (thick tantalum) side as expected

- Measured points were imported into MATLAB for surface fitting
Curve fitting

- Ignore tantalum sides and outer 5mm tungsten (edge effects)

- Spherical fit to upper surface (thick Ta) and lower surface (thin Ta)
  - Good fit ($R^2 = 0.990$)
  - Fit radius of curvature = 11.4m upper, 10.4m lower

### Upper surface

### Lower surface
Comparison with Theory

• Compare fit and simulated radii of curvature
  – Estimates lock-in temperature at 385-450°C
  – To produce the measured deflection the tantalum must have yielded
Future Work

• Neutron diffraction experiment on ISIS Engin-X instrument
  – Builds on previous work by Yanling Ma et al. on a TS1 plate*
    • Previous results suggest tantalum has yielded, but not enough data to confirm
    • Demonstrated that neutrons will be able to pass through our sample

• Re-measure deflection in a few years to see if stress has relieved
  – Strip manufactured last year, no stress relieving observed so far
  – However cyclic stress relieving may occur in beam?

Implications for ISIS Targets

• Appears to confirm our assumption that HIPing produces a residual stress large enough to yield the tantalum, i.e. HIPing rather than applied beam is the largest source of stress

• High tensile stress will reduce fatigue life of the cladding, although we currently have a large safety factor even with this included
  – Limited data on radiation damage and fatigue effects in tantalum
  – If tantalum ductility is lost this may present a problem

• Continuing to develop our understanding of failure modes will enable more optimised targets and higher beam powers in future
Conclusions

• Residual stress due to HIP process has been measured by a simple, mechanical method

• This will be followed up with neutron diffraction measurements on the same sample

• Measured residual stress is very high, therefore it is important to include this in any Ta-clad W target analysis

• We were able to accurately simulate the deflection of an asymmetric-clad strip by assuming a lock-in temperature of 385-450°C
Back-up slides
TS1 FEA Simulation – Setup

**TS1 Target CAD Model**

**FEA mesh for plates 1 and 2 (quarter model)**

**FLUKA heat deposition data**

**Thermal result (200°C max)**
TS1 FEA Simulation – Results

- Model of ISIS TS1 target plates 1 and 2
  - HIP residual stress assuming 500°C lock-in temperature
  - Thermal stress due to steady-state proton beam
  - Simulated tantalum plasticity assuming 200MPa yield strength

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Stress (Pa)</th>
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<tbody>
<tr>
<td>200uA Beam</td>
<td>127 MPa</td>
</tr>
<tr>
<td>HIP Residual Stress</td>
<td>200 MPa</td>
</tr>
<tr>
<td>HIP + 200uA Beam</td>
<td>79 MPa</td>
</tr>
</tbody>
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Beam heating partially relieves the residual HIP stress, as the unstressed state for the target is now uniformly at 500°C.

Results are similar for other ISIS targets:
- Tungsten yield stress is 550MPa
- Tantalum strain-to-failure is around 30-40%

<table>
<thead>
<tr>
<th></th>
<th>TS1</th>
<th>TS2</th>
<th>TS1 Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten Stress [HIP+Beam] (MPa)</td>
<td>207</td>
<td>191</td>
<td>165</td>
</tr>
<tr>
<td>Tantalum Stress [HIP+Beam] (MPa)</td>
<td>200*</td>
<td>200*</td>
<td>200*</td>
</tr>
<tr>
<td>Tantalum Total Strain (%)</td>
<td>0.40%</td>
<td>0.38%</td>
<td>0.42%</td>
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</table>

*200MPa is the yield stress of tantalum

No failure of the tungsten core is expected – the main concern is to ensure integrity of the cladding.
Measuring the Residual Stress

- This analysis depends entirely on the assumed value of lock-in temperature, which cannot be measured directly.

- The Engin-X instrument at ISIS used neutron diffraction to make preliminary measurements of residual stress in a clad ISIS plate.*

Measuring the Residual Stress

- Neutron diffraction measures spacing between atoms and uses this to determine elastic strain
  - Cannot measure plastic strain by neutron diffraction

- Measured elastic strains are broadly consistent with the cladding being at the yield stress as predicted – however the experiment did not measure all three directions so this cannot be confirmed

Engin-X Strain Result (Y direction)

\[ \approx 600 \text{ Microstrain} \]

\[ -300 \text{ Microstrain} \]

ANSYS Simulation of Engin-X Sample

\[ 662 \text{ Microstrain} \]

\[ -749 \text{ Microstrain} \]