Thermo-Mechanical Analysis of ISIS TS2

Spallation Target

Dan Wilcox

High Power Targets Group, Rutherford Appleton Laboratory

5th High Power Targetry Workshop, Fermilab

21/05/2014
ISIS Overview

Synchrotron
- 800MeV proton energy
- 200µA beam current (160kW power)
- Pulses at 50Hz

Target Station 1
- Receives 4 of every 5 beam pulses (40Hz)
- 160µA beam current (128kW power)
- Target: tungsten plates

Target Station 2
- Receives 1 of every 5 beam pulses (10Hz)
- 40µA beam current (32kW power)
- Target: solid tungsten rod
Background

- Aim: model the operating condition of the current ISIS TS2 target
  - Identify factors limiting target lifetime
  - Mk II target had to be replaced after radioactive material (thought to be tungsten) was detected in the cooling water
  - Inform design of future targets, e.g. TS1 upgrade
Overview of Beam-Induced Stresses

- Must also consider pre-stress from manufacturing methods

Acoustic waves due to sudden heat load

'stress-waves'

Periodic stress due to beam pulse

Average stress over time

Stress

Time

many seconds to reach quasi steady-state

'transient' stress

'steady-state' stress

0.1 sec

~ 10 µsec

Image credit: Peter Loveridge, HPTG
Modelling Beam Stresses

- **Steady State and Transient**
  - Full 3D geometry
  - Conjugate heat transfer for steady state
  - HTC assumed constant during transient model
  - Thermal results input to structural model

- **Stress waves**
  - 2D model in ANSYS Classic, many time steps required
  - Inertia effects included (dynamic stress response)
Summary of Stress Results at the Target Nose

Yield Stresses
- \( W \) Yield \( \approx 550 \text{ MPa} \)
- \( Ta \) Yield \( \approx 160 \text{ MPa} \)

\( W \sim 30 \text{ MPa} \)
\( Ta \sim 12 \text{ MPa} \)

\( W \sim 30 + 19 + 157 = 206 \text{ MPa} \)
\( Ta \sim 12 + 10 + 90 = 112 \text{ MPa} \)

\( W \sim 30 \text{ MPa} \)
\( Ta \sim 12 \text{ MPa} \)

\( W \sim 19 \text{ MPa} \)
\( Ta \sim 10 \text{ MPa} \)

many seconds to reach quasi steady-state

\( W \sim 157 \text{ MPa} \)
\( Ta \sim 90 \text{ MPa} \)

Time

Stress

\( \sim 10 \mu\text{sec} \)

'rest-waves'

' transient stress'

'Steady-state stress'
Pre-Stress: the HIP Process

• Hot Isostatic Press (HIP) used to diffusion bond tantalum to tungsten
  – Tungsten core sealed inside tantalum ‘can’
  – Assembly heated to ≈1200°C
  – Pressure of ≈140MPa applied to force parts together until they bond
  – Gradually returned to room temperature and pressure, then machined to final size

• Results in significant pre-stress
  – High pressure deforms tantalum can, but this occurs above annealing temperature
  – Cooling causes shrink-fit residual stress (tantalum contracts more than tungsten)
  – Stresses thought to ‘lock in’ at around 500°C
  – Heating in an impure environment will affect material properties – getter foils will reduce but not eliminate this

[Diagram of HIP assembly components]

Components of HIP assembly
Including Plasticity

- Bilinear material model applied for tantalum
- ‘Kinematic Hardening’ behaviour selected
  - An increase in yield stress in one direction is compensated for by a decrease in yield strength in the opposite sense (Bauschinger effect)
  - The total linear stress range is equal to twice the yield stress

**Tangent modulus = 1GPa**

**Yield Stress = 200MPa**

ANSYS material property “Bilinear Kinematic Hardening”

**Kinematic Hardening Model**
Combined Pre-Stress and Beam Heating

- 3D geometry in ANSYS Mechanical – target core only
- Stress wave effects were not included
- Assuming HIP does not affect heat transfer properties, thermal results do not change
- Static structural model with multiple load steps:
  1. The model starts in an unstressed state at 500°C
  2. A body temperature of 20°C is applied – resulting in HIP stress
  3. The model is heated to the steady state temperature
  4. Two beam pulses are applied
Combined Pre-Stress and Beam Heating

Stress and strain components at the target nose
Steady State Results with Pre-Stress

\[ \sigma_{\text{max}} = 207.6 \text{MPa} \]

Von Mises Stress in Tantalum

\[ \varepsilon_{\text{max}} = 0.0025 \]

Equivalent Plastic Strain in Tantalum

Geometry features around cladding front end

Areas of maximum steady state plastic strain
Steady State Plastic Strain

In cladding tube:
Elastic strain = 0.0011
Plastic strain = 0.0017
Total strain = 0.0028 (0.28%)

- Not enough to cause structural failure

Tensile test data for post-HIP Tantalum, carried out by Eamonn Quinn of ISIS
Combined Pre-Stress and Beam Heating

**Von Mises Stress (MPa)**

- **Stress**

**Analysis Time (arbitrary)**

- **Elastic/Plastic Transition**

**Strain (**)**

- **Elastic Strain**
- **Plastic Strain**
- **Total Strain**

*Stress and strain components at the target nose*
Strain Components During Pulsed Operation

Elastic Strain

$$\varepsilon = 1.0786 \times 10^{-3}$$

Plastic Strain
Transient Model with Pre-Stress and Bilinear Materials

Stress/strain plot at the target nose
Comparison of Cladding Tube and Target Nose

![Graph comparison of total strain vs. analysis time and von mises stress vs. total strain. The graph shows the comparison between Cladding Tube and Target Nose.](image-url)
Fatigue Analysis

- ISIS beam data suggests there are 0.6 beam trips per hour, or one trip every 60000 pulses
  - Number per year estimated based on frequency and average facility uptime

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Beam Pulse</th>
<th>Beam Trip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [Hz]</td>
<td>10</td>
<td>0.00017</td>
</tr>
<tr>
<td>Number Per Year</td>
<td>134,000,000</td>
<td>2230</td>
</tr>
</tbody>
</table>

- Stress waves ignored - material response is different on microsecond timescales

- Based on a simple total-life approach
  - Assumes an initially uncracked surface
  - Stress-life (high-cycle) fatigue

- Stress amplitudes are low, but average stresses are very high
  - Use a constant life diagram to see if this will be a problem
Stress amplitude = $\Delta\sigma/2$
Mean stress = yield stress − $\Delta\sigma/2$
Fatigue Analysis - Limitations

• Difficult to draw conclusions due to lack of material property data
  – No data could be found for tantalum fatigue
  – Very limited irradiation data
  – What will happen to HIPed, yielded, irradiated tantalum under periodic loading?

• The effect of stress waves is still unknown
• Are we including plastic effects in the right way?
• Stress concentration on cladding tube

**Graphs:**
- **ISIS target cut up at FZ-Juelich**
- **Specimen from STIP-II at PSI**
- **Neutron irradiated specimen from HFIR at ORNL**


Conclusions on TS2 Target

• HIP pre-stress looks like the most significant stress component
  – This will be validated against experiments on the ISIS instrument Engin-X, data analysis is currently underway

• Current theory is that fatigue failure of tantalum cladding will be the limiting factor of target lifetime
  – Tensile pre-stress and radiation embrittlement will make the fatigue situation worse
  – Irradiation creep and stress relaxation may reduce the average stress?
  – TS1 has much lower periodic loading, and has proven very reliable
  – Stress concentration on cladding tube will be removed on future targets

• Beam accident case is another possible explanation
  – Current instrumentation will not immediately detect an over-focused beam
  – Thought to be more of a risk for TS1 than TS2

• Understanding is limited by availability of material property data
  – There are spent ISIS targets available for PIE


Relevance to TS1 Upgrade

• Aim: Design a target which combines the neutronic performance of TS2 and the reliability of TS1
  – Designed in collaboration with ISIS Neutronics and ISIS Target Engineering

• Reliability is the top priority

• Neutronic optimisation goals include thinner cladding and fewer plates
  – Difficult to set material limits without fully understanding the operating condition of current targets
  – Better understanding of current target issues will ultimately allow for more highly optimised targets in future