Irradiation Induced Failure Analysis of NuMI Target

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Dec 11, 2019
Outline

• Background NTO2 Target fin
• Fin material properties and response under irradiation
• Swelling empirical formula
• Finite element implementation and results
• Failure analysis
Background - NT02 Target Fin

Segmented Fins - 47 pieces

Individually target fin
20mm x 15 mm x 6.6 mm

Material: POCO ZXF 5Q graphite
Isotropic
Background- Fracture fin

Beam Parameters:
- Energy: 120 GeV
- Beam sigma: 1.1 mm
- Spill duration: 10 μsec, $4 \times 10^{13}$ protons/pulse
- Duty cycle: 1.87 sec
- Peak fluence: $8.6 \times 10^{21}$ protons/cm$^2$

Bulk swelling of ~2%
POCO ZX F 5Q Graphite microstructure

- Less Mrozowski cracks
- Randomly oriented grains
  - isotropic
- Pores & particles ~ microns
- Particles packed with many grains
  - Fine grains (~30nm)

Irradiation Induced Failure analysis NUMI Target
Graphite Swelling $\rightarrow$ Fluence factor

C-axis expansion is more than a-axis contraction

Swelling $\rightarrow f(\text{fluence, temperature})$

- More swelling at lower temperature
Graphite Swelling $\rightarrow$ XRD - POCO ZXF5Q

C-axis expansion is more than a-axis contraction $\rightarrow$ net expansion

Interstitial $\rightarrow$ expansion

Vacancy $\rightarrow$ contraction
Swelling factor function

Local Swelling factor
= \text{f(fluence)} \times \text{g(temperature)}

\text{sw}(\varnothing, T) = \text{f}(\varnothing) \cdot \text{g}(T)

Initial guess for f(\varnothing)

f(\varnothing) = \exp \{-b(\frac{u}{\sigma})^2\}
Swelling factor function

\[ \partial(s_w) = g(T) \cdot \partial f(\varnothing) + f(\varnothing) \cdot \{ \partial g(T) \} \]

At constant fluence, swelling factor follows a polynomial function with temperature (next slide).

Attempting to find form of the function from the swelling trend.
Swelling → Temperature Factor

Pronounced swelling at lower temperatures

\[ \partial g(T) = 2 \times 10^{-7} T^3 - 7 \times 10^{-5} T^2 + 1.5 \times 10^{-3} T + 1.0083 \]

NTO2 steady state operating temperature range

1 MWD = 7e16 nvt
Steady State Thermal Analysis

1/8th symmetry model

(a)

Beam direction

Path-x
Path-y

87.04 Max
80.702
74.365
68.027
61.689
55.351
49.013
42.676
36.338
30 Min

Transient Temp. at beam center

Time, sec

Temperature, C

Steady state thermal

Temperature, C

y = -0.0891x^3 + 1.1482x^2 - 3.7969x + 0.4138 + 87.701

R^2 = 1

Distance from beam center, mm

Average irradiation temperature 30C~87C
Swelling factor $\rightarrow$ combined function of fluence and temperature

$$sw(u, T) = C \cdot \exp\left\{ -b \left( \frac{u}{\sigma} \right)^2 \right\} \cdot \{5 \times 10^{-8} \ T^4 - 2 \times 10^{-5} \ T^3 + 5 \times 10^{-4} \ T^2 + 1.0083 \ T + 1 \}$$

Swelling is reduced at center due to relatively high irradiation temperature
XRD data NTO2

Assumption
Experimental swelling = \partial(d/d0)

XRD scan spot size is 50\mu m x 50\mu m x 10\ mm
In FEA, element size is made \sim 50\mu m so that it would match to XRD scan volume

\[ \Phi_o \sim 8.6 \times 10^{21} \text{ p/cm}^2 \]
Determining Swelling Coefficient

<table>
<thead>
<tr>
<th>U (mm)</th>
<th>Temperature</th>
<th>sw</th>
<th>d-spacing</th>
<th>∂(d/d0)</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>88</td>
<td>0.779</td>
<td>3.621</td>
<td>0.074481</td>
<td>0.000894</td>
</tr>
<tr>
<td>1.1</td>
<td>84</td>
<td>0.686</td>
<td>3.618</td>
<td>0.073591</td>
<td>0.001073</td>
</tr>
<tr>
<td>2.2</td>
<td>81</td>
<td>0.442</td>
<td>3.542</td>
<td>0.051039</td>
<td>0.001211</td>
</tr>
<tr>
<td>3.3</td>
<td>78</td>
<td>0.210</td>
<td>3.45</td>
<td>0.023739</td>
<td>0.001245</td>
</tr>
</tbody>
</table>

\[ \text{sw}(u, T) = C \exp\left\{-b \left(\frac{u}{\sigma}\right)^2\right\} \cdot \{5 \times 10^{-8} T^4 - 2 \times 10^{-5} T^3 + 5 \times 10^{-4} T^2 + 1.0083T + 1\} \]

Equating \( \text{sw}(u, T) \) to \( \partial(d/d0) \) \( \Rightarrow \) \( C \)

Multi-variate regression analysis:
Varying “b” and “σ” to get C curve as flat as possible
\( \Rightarrow b = 0.155, C = 0.00107, \sigma = 1.11 \)

\[ \text{sw}(u, T) = 0.0011 \exp\left\{-0.155 \left(\frac{u}{1.11}\right)^2\right\} \cdot \{5 \times 10^{-8} T^4 - 2 \times 10^{-5} T^3 + 5 \times 10^{-4} T^2 +1.0083T + 1\} \]
Young’s Modulus variation with Fluence $\phi$

"$E$" varies with $\phi$

$\phi$ varies with location.

$\phi = \phi_0 \exp \{-0.5(u/1.1)^2\}$

This two relationship is used to map "$E$" as a function of location

$E=E_0[1+f_1(\phi)]$

Peak fluence $\phi_0$ $8 \times 10^{20}$ p/cm$^2$
Model- Geometry

1/8th Model → Symmetric in x, y, and z direction

Cooling water temperature 30°C
Fixed support

Beam along Z-direction
Gaussian Beam in x-y

Symmetric Boundary Condition on x, y and z plane

\[ u_{i,i} = 0 \]
\[ \theta_{i,j} = 0 \quad i \neq j \]
\[ = \text{free} \quad i = j \]
FE Model

Larger temperature gradient within beam center

Mesh Optimization
- Finer elements at the beam center
- Progressively larger elements
- 30 elements within 1-σ of beam
- Minimum distorted elements
- Curvature and proximity refinement.

15000 elements  68,0000 nodes

Check element quality
High Jacobian ratio $\rightarrow$ spurious stress values

Keep $J-R$ as close to 1
$JR > 10$ can lead to increase in stress by 20%

Jacobian Ratio (Gauss points)
FEM Implementation of Empirical Formula

Total Strain \( \varepsilon = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{pl} + \dot{\varepsilon}_{cr} + \dot{\varepsilon}_{th} + \dot{\varepsilon}_{SW} \)

Linear swelling model

Swelling Strain

\( \dot{\varepsilon}_{SW} = C \Phi_t \)

\( \dot{\varepsilon}_{SW} = \varepsilon_{SW} (t, T, \Phi_t, \sigma) \)

\( \{ \varepsilon^{SW} \} = [ \varepsilon_{SW} \varepsilon_{SW} \varepsilon_{SW} 0 0 0 ]^T \)

No shear, only volume change

APDL Scripts

```
! Unirradiated formulation
load=10.0; mask=4; locax=13
!OR
*get, elem_count, elem, count curr_elem=0
*do,1,1,elem_count
  curr_elem=next(elem_count)
  x_loc=centx(curr_elem)
  y_loc=centy(curr_elem)
  ! Defining Young's as a 2-D sp
  sigma=1.1
  flu_local=peak_flu*exp(-0.5*mod_fact1*(flu_local/lambda))
  mod_fact1=flu_local/lambda
  mod_fact2=flu_local/lambda
  mod_fact3=flu_local/lambda
  mod_fact4=flu_local/lambda
  mod_fact5=flu_local/lambda
  flu_fact=scale*E0*(1+mod_fact1)*mod_fact2
  flu_value(i)=flu_fact
```
Simulation Frame-work

After years of operation

New

Deformed

One beam pulse

Dynamic stresses

Beam Parameters
- Number of protons pulse: $4 \times 10^{13}$
- Pulse duration: 10 µsec
- Beam $\sigma$: 1.1 mm
- Energy deposited/pulse: 480 J/cm$^3$

Steady State Thermal Analysis

Static structural analysis
- swelling factor as function of fluence, temperature $sw(\varnothing, T)$
- Young’s modulus = $f(\text{fluence})$
- CTE $\rightarrow f(\text{Temperature})$
- Solve stress, strain, deformation states

Transient Thermal-Dynamic analysis
- Initialize domain with $\sigma, \varepsilon, u$ from static structural
- Turn off $g(T)$ portion of $sw(\varnothing, T)$
- Young’s modulus = $f(\text{fluence})$
- CTE $\rightarrow f(\text{Temperature})$

Few micro-secs of high temperature is not enough to influence any swelling (annealing)
Static Structural analysis – $\sigma_{yy}$ Distribution

Without Swelling

Beam direction

With Swelling

Beam direction

Path-x

Tensile

Compressive

2.45 mm

State just before beam pulse after number of years of exposure to neutrons

Irradiation Induced Failure analysis NUMI Target
Swelling formulation raised the stress level up to 150 MPa.
Simulation Validation - amount of swelling

Deformed location

From Simulation
\[(3.323-3.3)*100/3.3 = 0.7\%\]

Observed bulk swelling at that location \(\sim 2\%\)

Difference of factor of 2 is not too bad…?
- Measurement technique
- Assumptions in empirical formulation
Simulation Validation - Stress states

XRD Scan NTO2

Transition of d-spacing state of stress from compression to tension

Predicted by swelling simulation

Undeformed crystallite d-spacing 3.37
Simulation Validation- Mohr-Coulomb’s factor of safety

\[ F_{safety} = \left( \frac{\sigma_1}{\sigma_{ut}} + \frac{\sigma_3}{\sigma_{uc}} \right)^{-1} \]

FS distribution

FS <1

Probable crack initiation sites
Fractography suggest crack starting from inside and propagating outward

79 MPa 175 MPa
Dynamic stresses - $\sigma_{yy}$

R = -1 Sever form of fatigue

Two fatigue loading 1) 11MPa with 1.87sec 2) 5MPa with 4µsec

Fermilab
Fatigue Crack growth stages

Crack initiation → significant portion of fatigue life

Cyclic Max shear stress → intrusion protrusion of slip lines

Sharp crack tip

Tensile stress → microcrack growth

compressive stress in (R<-1)
Regain sharp crack

Pores and microcracks → local stress concentration
Crack initiation in crystallites → nano-scale, slow
Crack growth/propagation between the particles → micro-scale, fast
Conclusions

- Thermal stresses alone could not have caused crack
- Implementing swelling strain effectively raised the stress state close to failure strength.
- Simulation could explain probable crack initiation region
  - Regions with Factor of safety <1
- Dynamic stresses due to beam heating → potential fatigue crack
  - High amplitude low frequency → 11 Mpa 15 million cycles per year
  - Low amplitude high frequency → 5 Mpa Gigacycles per year
  - Regions of complete load reversal at about 2.45mm from beam center
- Graphite has low endurance limit ~14 Mpa (@1 million cycle)
  - Low amplitude gigacycle load can cause fatigue failure
Summary

- Developed an empirical formula for local swelling (Temp, fluence)
- Simulation results bulk swelling reasonable agreement with measurement
- Combined swelling stress and dynamic stress due to beam loading caused failure

Did not take into account
- Stress, creep effect on swelling.
- Dislocation distribution and type, grain boundary segregation etc.

In Future → Make the model predictive
- Obtain parameters from mechanism of swelling rather than XRD
Thank You!