Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Irradiation Induced Failure Analysis of NuMI Target

Sujit Bidhar

Dec 11, 2019

6th RaDIATE Collaboration Meeting

The banner features a background of a particle accelerator tunnel with a blue and orange diagonal stripe on the left. The text "6th RaDIATE Collaboration Meeting" is written in white, bold, sans-serif font.

Radiation Damage in Accelerator
Targets Environments

6th RaDIATE Collaboration Meeting

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of

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

Material : POCO ZXf 5Q graphite
Isotropic

Background- Fracture fin

Beam Parameters:

Energy : 120 GeV

Beam sigma : 1.1mm

Spill duration : 10μsec, 4×10^{13} protons/pulse

Duty cycle : 1.87sec

Peak fluence : 8.6×10^{21} protons/cm²

Bulk swelling of ~2%

POCO ZXf 5Q Graphite microstructure

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

Graphite Swelling → Fluence factor

XRD – Pyrolytic carbon

C-axis expansion is more than a-axis contraction

Swelling → f(fluence, temperature)

- More swelling at lower temperature

Graphite Swelling → XRD- POCO ZXF5Q

C-axis expansion is more than a-axis contraction → net expansion

Swelling factor function

Local Swelling factor
= $f(\text{fluence}) \cdot g(\text{temperature})$
 $sw(\emptyset, T) = f(\emptyset) \cdot g(T)$

Initial guess for $f(\emptyset)$

$$f(\emptyset) = \exp \{ -b(u/\sigma)^2 \}$$

Swelling factor function

$$\partial(\text{sw}) = g(T) \cdot \partial f(\emptyset) + \underline{f(\emptyset) \cdot \{\partial g(T)\}}.$$

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

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

Pronounced swelling at lower temperatures

Steady State Thermal Analysis

1/8th symmetry model

Average irradiation temperature 30C~87C

Swelling factor → combined function of fluence and temperature

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

Swelling is reduced at center due to relatively high irradiation temperature

XRD data NTO2

Assumption
Experimental
swelling = $\partial(d/d_0)$

XRD scan spot size is $50\mu\text{m} \times 50\mu\text{m} \times 10\text{mm}$

In FEA, element size is made $\sim 50\mu\text{m}$ so that it would match to XRD scan volume

Determining Swelling Coefficient

U (mm)	Temperature	sw	d-spacing	$\partial(d/d_0)$	C
0	88	0.779	3.621	0.074481	0.000894
1.1	84	0.686	3.618	0.073591	0.001073
2.2	81	0.442	3.542	0.051039	0.001211
3.3	78	0.210	3.45	0.023739	0.001245

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

Equating $sw(u, T)$ to $\partial(d/d_0) \rightarrow C$

Multi-variate regression analysis:

Varying “b” and “σ” to get C curve as flat as possible

$\rightarrow b = 0.155, C = 0.00107, \sigma = 1.11$

$sw(u, T)$

$$= 0.0011 \cdot \exp\left\{-0.155 \left(\frac{u}{1.11}\right)^2\right\} \cdot \{5 \times 10^{-8} T^4 - 2 \times 10^{-5} T^3 + 5 \times 10^{-4} T^2 + 1.0083T + 1\}$$

Young's Modulus variation with Fluence $\emptyset$

“E” varies with $\emptyset$
 $\emptyset$ varies with location.

$$\emptyset = \emptyset_0 \exp \{-0.5(u/1.1)^2\}$$

} This two relationship is used to map
 “E” as a function of location

$$E = E_0 [1 + f_l(\emptyset)]$$

Model- Geometry

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

Symmetric Boundary Condition on x, y and z plane

$$\begin{aligned} u_{i,i} &= 0 \\ \theta_{i,j} &= 0 \quad i \neq j \\ &= \text{free} \quad i = j \end{aligned}$$

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 68,000 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%

FEM Implementation of Empirical Formula

Total Strain $\epsilon = \epsilon_{el} + \epsilon_{pl} + \epsilon_{cr} + \epsilon_{th} + \epsilon_{sw}$

Linear swelling model $\dot{\epsilon}_{sw} = C \dot{\Phi}_t$

Swelling Strain $\epsilon_{sw} = \epsilon_{sw}(t, T, \Phi_t, \sigma)$

tb,swell,matid,,,line
tbdata,1,0.1

$\{\epsilon^{SW}\} = \begin{bmatrix} \epsilon_n^{SW} & \epsilon_n^{SW} & \epsilon_n^{SW} & 0 & 0 & 0 \end{bmatrix}^T \Rightarrow$ No shear, only volume change

APDL Scripts

```
currnode1=0
tmax=0
*do,i,1,numnodes
currnode1=ndnext(currnode1)
*get,tem,node,currnode1,ntemp
*if,tem,gt,tmax,then
tmax=tem
*endif
*enddo
max_temp=tmax
*dim,locax,array,numnodes
*dim,flu_value,array,numnodes
!Swelling only factor
peak=0.107
sigma=1.11
b=0.155
currnode=0
*do,i,1,numnodes
currnode=ndnext(currnode)
l_x=nx(currnode)
l_y=ny(currnode)
flu_fact=exp(-b*(l_x**2+l_y**2))
locax(i)=l_x
flu_value(i)=flu_fact
```

APDL Scripts

```
Eo=14.5e3 ! Unirradiat
nus=0.3 ! Poisson's
sigma=1.1
lambda=13
k=1.3
c=1.5
peak_flu=8
scale=1.0

!elem_count=elmidqr(0,i4)
!OR
*get,elem_count,elem,,count
curr_elem=0

*do,i,1,elem_count
curr_elem=elnext(curr_elem)
x_loc=centrx(curr_elem)
y_loc=centry(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_fact2=(flu_local/lambda)
mod_fact3=exp(-mod_fact2)
mod_fact=c*mod_fact1*mod_fact3
Es_mod=scale*Eo*(1+mod_fact)
```

Simulation Frame-work

Steady State Thermal Analysis

Static structural analysis

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

Few micro-secs of high temperature is not enough to influence any swelling (annealing)

Beam Parameters

Number of protons pulse: 4×10^{13}
Pulse duration : 10 μsec
Beam σ : 1.1 mm
Energy deposited/ pulse : 480 J/cm³

Transient Thermal-Dynamic analysis

- Initialize domain with σ, ϵ, u from static structural
- Turn off $g(T)$ portion of $sw(\Phi, T)$
- Young's modulus = $f(\text{fluence})$
- $CTE \rightarrow f(\text{Temperature})$

Static Structural analysis – σ_{yy} Distribution

With Swelling

Without Swelling

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

Simulation validation- failure strength

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 ~ 2%

Difference of factor of 2 is not too bad...?

- Measurement technique
- Assumptions in empirical formulation

Simulation Validation- Stress states

XRD Scan NTO2

Simulation Validation- Mohr-Coulumb's factor of safety

FS distribution

FS < 1

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

79 MPa 175 MPa

Probable crack initiation sites

Fractography suggest crack starting from inside and propagating outward

Dynamic stresses- σ_{yy}

R=-1 Sever form of fatigue

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

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 (@1million 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!