Post Irradiation Examination of an Alloy 718 Beam Window

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Outline

- Isotope Production Facility
- Cutting of Window and Dimensional Measurements
- Calculation of Dose and Irradiation Temperature
- Shear Punch Testing
  - Trepanning of Specimens
  - Dose/Irradiation Temperature vs. Location
  - Shear Punch Testing and Data
- TEM Analysis
- Comparison to previous test results
- Summary
H+ is produced at the source injector, accelerated through DTL, diverted to IPF at the TR region through magnets, and ended on targets inside a heavily shielded target irradiation chamber.
The proton beam is delivered via a vacuum beam pipe. Inconel 718 beam window isolates the beam pipe (under vacuum) and the target irradiation chamber (15 psig of cooling water).

Present design limit for window is 5 years and would like to increase that limit through analyzing properties after 5 years of operation.
Cutting off the Window

Window was cut from beam tube remotely in the corridor of the CMR Wing 9 hot cells.

Then, the window was placed into an individual hot cell for analysis and sample preparation.
Dimensional and Dose Measurements on Window

GAFCHROMIC HD-810 dosimetry film was used to measure the absorbed dose of high energy photons from the activated beam window.

Beam window deformed 1.5mm into the vacuum side.

Rastered beam profile shows a Gaussian distribution and the highest dose region corresponds to the darkest blue region on the Gafchromic film.
Temperature and Dose Map

- 9.5 dpa
- 12.5 dpa
- 2-5 dpa
- 0.25-1.5 dpa

Temperature Scale:
- 109°C
- 25°C
Beam profile was superimposed on the window to determine the cutting plan as a function of radiation dose (dpa).

3-mm OD samples were cut with a Mill machine. A total of 3 cutting bits were spent to cut out 20 numerical samples (1-20) and 5 alphabetical samples (A, B, C, E, and F).

Cut-out samples were polished and thinned from on both sides to 0.254 mm thickness.

The shear punch testing for the following samples were completed as a function of radiation dose (dpa):

- 2 controls samples of unirradiated Inconel 718
- 1-6, 8, 9, 10-13, 15-16, 17-18, 19-20, A-C, and E
Trepanning 3 mm Diameter Samples from Window
Shear Punch Testing Equipment at CMR Hot Cell

- Performed 25 shear punch tests on 3 mm diameter specimens.
- Tested at initial strain rate of $5 \times 10^{-4}/s$.
- Tested at in ultra high purity argon.

Shear Punch Set-up

Loading sequence

Typical shear punch specimen
Control Material Tensile Tests vs Shear Punch

- UTS correlation - 1.28
- Yield Correlation - 1.77
- Lit values 1.4, 1.73

Toloczko & Kurtz

435 MPa Yield

900 MPa UTS

700 MPa UTS

230-250 MPa 1% shear yield
Shear Punch, Outer to Inner

Control + 4 regions

Effective Shear Stress (MPa)

Displacement (mm)

0 0.05 0.1 0.15 0.2 0.25 0.3

0 200 400 600 800 1000

- High Rad 3
- High Rad 4
- Outer Ring 17
- Outer Ring 18
- Beam Center 1
- Beam Center 2
- Outside Collimator 10
- Outside Collimator 11
- Control

0.5dpa
2.55dpa
11 dpa
12.5 dpa
Control
Comparison of Shear Stress/displacement Curves

Dose = 12.5 dpa  
Tirr = 109C

Dose = 0.5 dpa  
Tirr = 50C
Optical Images of Exit side of Shear Punch Specimens

Control Material

Dose = 12.5 dpa
Inconel 718 Solution Annealed-unirradiated

Bright field TEM images showing dislocations and some precipitates
TEM Analysis of Irradiated Alloy 718 Samples

- 0.5 dpa at 50°C
- 12.5 dpa at 109°C
Previous Results on Proton Irradiated Annealed 718 SPF

- Inconel 718 SPF samples irradiated in STIP-II
- Samples show good retention of ductility even with much higher helium levels
Summary of Tensile Results

- All samples display ductility in both yield vs UTS and optically.
- Samples taken in outer ring and outside collimator have a higher yield and UTS than control or high radiation dose samples.
- Increased hardening appears to be a combination of increased defect density, bubble density and second phase precipitation.
- From these results we are confident to push lifetime out to ~17 dpa.
- Further analysis required to understand bubble formation in low dose samples.
Comparison to previous tensile results

- Farrell et al. (03) shows increase from 350 MPa to 900 MPa for irradiation at 50-100C for a dose of 1.2 dpa
- STIP-II shows increase from 600 to 1200 MPa at 183C and 600 to 1100 MPa at 382C to doses of 7.8 and 18 dpa respectively
- IPF data shows increase from 450 to 1100 MPa at 9 dpa and 850 MPa at 11-12 dpa. Also an increase to 1100 MPa is observed at 2-4 dpa.
Shear Punch Results

Almost All Middle Range

High Rad Ring

Around the Outside of Collimator

Effective Shear Stress (MPa)

Displacement (mm)
Dark and bright field TEM images showing smaller precipitates and dislocations.
Unirradiated Inconel 718 Ni, Mo, Nb (some Co, Cu) rich precipitate
Inconel 718 #5 ~14 dpa @109°C
Irradiation Damage and Replacement

- Beam transmission through the window incurs heating causing thermal stress.
- Beam irradiates the window causing mechanical properties to change.
- Beam window design criteria is 20 dpa (displacement per atom). Beam window reached the end of its life.
- Estimate dose rate is 100 R/hr at contact without shielding and highly contaminated.
- We replaced window in March 2010, stored at Area A and shipped to CMR in November 2010.

Calculated Von Mises stress under pressure and thermal load at the center of the target is ~ 510 MPa. Window will fail when Von Mises stress > the yield strength.
Outline of beam collimator is evident on beam window.

Approximate dimensions are 10 cm diameter x 0.5 mm thick.
Machined Window
Optical Images of Control Sample #6 (Unirradiated)
Optical Images of Sample # 8 (High Radiation Ring)
Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

0.5 dpa at 50°C

12.5 dpa at 109°C

Unirradiated (SA)

Unirradiated-PH


0.5 dpa at 30-60°C

0.6 dpa
Inconel 718 #19 ~ 0.5 dpa @50°C

- Bright field TEM images showing dislocation loops.
- Under-focus TEM images on the right are showing a high density of bubbles/voids that are on the order of 5x10^9 nm.
- 0.25-1.5 dpa
Inconel 718 #19 ~ 0.5 dpa @50°C γ″ precipitates
0.5 dpa 50°C
Inconel 718 #16 ~ 2.5 dpa @ ~40°C
Bright field TEM images showing dislocations, precipitates are not detected?
Inconel 718 #E ~11 dpa @~75°C
- Loop density
- Loop size
- Loop size and density